A Game-Based Decision Support Methodology for Competitive Systems Design

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A Game-Based Decision Support Methodology for Competitive Systems Design

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Para mis papás, Patricia y Sálvano, por todo...

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Simón, December 2008.

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LIST OF ACRONYMS

ALCCA	Aircraft Life-Cycle Cost Analysis
ANOPP	Aircraft Noise Prediction Program
BRAINN	Basic Regression Analysis for Integrated Neural Networks
CCD	Central Composite Design
CDF	Cumulative Distribution Function
CE	Concurrent Engineering
DoE	Design of Experiments
EDS	Environment Design Space
FAA	Federal Aviation Administration
FLOPS	Flight Optimization System
FPR	Fan Pressure Ratio
GE	General Electric
GTF	Geared Turbofan
HPCPR	High Pressure Compressor Pressure Ratio
HPCWc	High Pressure Compressor Mass Flow
HSCT	High Speed Civil Transport
IEDS	Iterated Elimination of Dominated Strategies
INCOSE	International Council on Systems Engineering
IPD	Integrated Product Design
IPPD	Integrated Product and Process Development
IPT	Integrated Product Team
JPD	Joint Probability Distribution
JPDF	Joint Probability Distribution Function

MADM	Multi-Attribute Decision-Making
MCPH	Maintenance Cost Per Hour
MCS	Monte Carlo Simulation
MoA	Matrix of Alternatives
MS	Modeling and Simulation
MTOGW	Max Takeoff Gross Weight
NASA	National Aeronautics and Space Administration
NE	Nash Equilibrium
NN	Neural Networks
NPSS	Numerical Propulsion System Simulation
OEC	Overall Evaluation Criteria
OPR	Overall Pressure Ratio
pax	Passenger
PCT	Project completion time
PDF	Probability Density Function
PW	Pratt and Whitney
QFD	Quality Function Deployment
RDS	Robust Design Simulation
RDTE	Research, Development, Testing and Evaluation
RFP	Request for Proposal
RR	Rolls Royce
RSE	Response Surface Equation
RSM	Response Surface Methodology
SP2	Strategy Prioritization and Planning

SWOT	Strengths, Weaknesses, Opportunities, and Threats
T4	Turbine Inlet Temperature
TOFL	Takeoff Field Length
TQM	Total Quality Management
TSFC	Thrust Specific Fuel Consumption
WATE	Weight Analysis of Turbine Engines
NPV	Net Present Value
α_{NF}	New project follower market advantage in similar project competition
α_{NL}	New project leader market advantage in similar project competition
$\mu_{N(D)}$	Natural Logarithm Mean for a New (or Derivative) PCT
σ_{DF}	Derivative project follower market advantage in differentiated project competition
σ_{DL}	Derivative project leader market advantage in differentiated project competition
$\sigma_{N(D)}$	Natural Logarithm Standard Deviation for a New (or Derivative) PCT
σ_{NF}	New project follower market advantage in differentiated project competition
σ_{NL}	New project leader market advantage in differentiated project competition
τ_{iN}	Sampled project completion time from firm i's derivative project probability distribution
τ_{iN}	Sampled project completion time from firm i's new project probability distribution
E_N	Ratio of firms' completion times for a derivative project
E_N	Ratio of firms' completion times for a new project
r_D	Market rewards available for a derivative project
r_N	Market rewards available for a new project

$T_{iN(iD)}$	Firm i's mean completion time for a new (or derivative) project

SUMMARY

This dissertation describes the development of a game-based methodology that facilitates the exploration and selection of research and development (R&D) projects under uncertain competitive scenarios. The proposed method provides an approach that analyzes competitor positioning and formulates response strategies to forecast the impact of technical design choices on a project's market performance.

A critical decision in the conceptual design phase of propulsion systems is the selection of the best architecture, centerline, core size, and technology portfolio. This selection can be challenging when considering evolving requirements from both the airframe manufacturing company and the airlines in the market. Furthermore, the exceedingly high cost of core architecture development and its associated risk makes this strategic architecture decision the most important one for an engine company. Traditional conceptual design processes emphasize performance and affordability as their main objectives. These areas alone however, do not provide decision-makers with enough information as to how successful their engine will be in a competitive market.

A key objective of this research is to examine how firm characteristics such as their relative differences in completing R&D projects, differences in the degree of substitutability between different project types, and first/second-mover advantages affect their product development strategies. Several quantitative methods are investigated that analyze business and engineering strategies concurrently. In particular, formulations based on the well-established mathematical field of game theory are introduced to obtain insights into the project selection problem. The use of game theory is explored in this research as a method to assist the selection process of R&D projects in the presence of imperfect market information. The proposed methodology focuses on two influential factors: the schedule uncertainty of project completion times and the uncertainty associated with competitive reactions.

A normal-form matrix is created to enumerate players, their moves and payoffs, and to formulate a process by which an optimal decision can be achieved. The non-cooperative model is tested using the concept of a Nash equilibrium to identify potential strategies that are robust to uncertain market fluctuations (e.g: uncertainty in airline demand, airframe requirements and competitor positioning). A first/second-mover advantage parameter is used as a scenario dial to adjust market rewards and firms' payoffs.

The methodology is applied to a commercial aircraft engine selection study where engine firms must select an optimal engine project for development. An engine modeling and simulation framework is developed to generate a broad engine project portfolio. The creation of a customer value model enables designers to incorporate airline operation characteristics into the engine modeling and simulation process to improve the accuracy of engine/customer matching.

Several key findings are made that provide recommendations on project selection strategies for firms uncertain as to when they will enter the market. The proposed study demonstrates that within a technical design environment, a rational and analytical means of modeling project development strategies is beneficial in high market risk situations.

Chapter I

INTRODUCTION

"It is this triple convergence-of new players, on a new playing field, developing new processes and habits for horizontal collaboration-that I believe is the most important force shaping global economics and politics in the early twenty-first century."

-Thomas L. Friedman

1.1 Research Motivation

The practice of engineering in society has evolved over the past half century because of a changing global arena. Although engineering remains the art and science of creating practical solutions, the *engineering process* of achieving these solutions has been redefined. In the aerospace community, many companies now design, manufacture, and sell their products by decentralizing their operations according to the U.S. International Trade Commission (2001). The Boeing 787 program for example, represents a network of the very best suppliers and has revolutionized the way in which aircraft are designed and built (Elmer Doty, 2007). The significant amount of resources required to produce large scale systems combined with potential market risks have engineers focusing on getting the design right early on.

The commercial aviation industry is an example of an evolving market where margins on regulations, environmental awareness, and life-cycle cost are having more leverage on the success of a program than at any other time in the past. One particular trend has emerged where large-scale airframe manufacturers offset design and production responsibilities to key global suppliers for the purpose of gaining market access to ultimately gain a competitive advantage when airlines in those markets consider purchasing new aircraft (National Research Council, 1999; U.S. International Trade Commission, 2001). Brandenburger and Nalebuff (1996) conclude that there is an important interdependence between manufacturers, suppliers and customers that should be considered when addressing market requirements. The investigation of these relationships and how they impact the aircraft engine design process is a motivating problem in this research.

The primary example application in this research is aircraft engine design. The commercial aircraft engine is an example of a complex system that is a key determinant in satisfying customer requirements. According to the U.S. General Accounting Office (2001), as the market becomes more uncertain, matching customer needs with available resources is a priority early in the design process. Engine companies make important strategic decisions in designing their engine core architectures because the risks in development costs and evolving customer requirements can likely collapse the entire business. Authors like Newhouse (1982) state that commercial aircraft and engine business sets itself apart from other industries because of the size of the risks and the costs that must be accepted. Greenwald (1981) recounts how the development and subsequent market failure of the Rolls Royce RB211-22 program for the Lockheed TriStar in the late 1960's was evidence of an attempt to guarantee performance requirements that ultimately could not be met.

There is a trend in the systems engineering community that involves synthesizing all parts relating to the system, from the performance (technical) to the customer (business). From this perspective, an engineer approaches a complex systems design problem *"in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect"* (Fossnes and Forsberg, 2006). The research conducted in this dissertation is focused primarily on investigating new techniques that link the technical aspects of engineering with the business aspects of the market. According to Newhouse (1982), a driving force in the market is that of competition where companies must constantly *"estimate market size over a period of ten to fifteen years, partly on the basis of how they see the economy and world politics evolving, and partly on the basis of the activities of their competitors"*. The fierce competition between Boeing and Airbus for global market share reinforces the importance of getting the design right early on because, as Kretschmer (1998) recounts, *"committing large chunks of a company's resources to a single investment project is always a risky undertaking. It becomes even riskier when a competitor is set to do the same thing and the market is unlikely to sustain two rival products"*.

Many authors agree that decisions made early in the design process have a lasting impact on the success of a program (Ettlie, 1997; Kirby, 2001; Mavris, Macsotai and Roth, 1998). The International Council on Systems Engineering (INCOSE) also mentions the consequences on life-cycle cost of making decisions early without the *"benefit of good information and analysis"* (Fossnes and Forsberg, 2006). In order to introduce these goals into the conceptual design process, technical and non-technical design factors have to be co-addressed early in design. In the aircraft engine industry, this will enable engineers to address questions like: How much design margin is sufficient in order to be competitive? How much growth potential is necessary to guarantee future sales? When is it better to take a "wait and see" approach to benefit from market uncertainty?

Although it may be difficult to answer these questions analytically, this challenge can be overcome with a framework that provides engineers with means to use decision-critical knowledge to model, structure, and interface multi-attribute decisions within the context of risk and uncertainty. With an increasingly uncertain and dynamic global marketplace and a rapid change of pace in consumer demand this framework must be anchored in strategic thinking.

This research proposes a systematic approach to competitive analysis that supports decision-making in the concept selection phase of large-scale systems. This enables decision-makers to explore design strategies and select the most optimum designs under the realms of competitive uncertainty and customer requirements evolution. Various concepts and techniques are borrowed from the mathematical discipline of game theory as means to facilitate the systematic exploration of strategic solutions.

The goal of this chapter is to establish the foundation for the motivation behind this research. The approach taken to narrow the scope of the problem is reflected in the structure of the chapter. The following sections begin with broad concerns in the conceptual design field and end with issues surrounding competitive analysis in engineering design. Observations are made at each stage and research objectives are presented at the end of the chapter.

1.2 A Strategic Approach to Aerospace Design

Engineering can be described as a way of manipulating nature to create something physical that has value to at least some segment of mankind. According to Hazelrigg (1996), *"The process of creating something physical requires allocation of nature's resources; therefore, engineering design is, essentially, the effective allocation of resources. The allocation of resources is, by definition, decision making"*. If the act of designing is a decision-making process then the process by which decisions are made is instrumental in understanding a design process. There are two key domains where decision-making is prevolent in systems engineering and is the core of this research. The first one is called *project planning and control* which describes how the creation of products and services is managed within a system's life-cycle. The second domain is the field of *systems engineering*. Since the creation of products arises from systems engineering it is important to understand how these two areas interact. A motivating interest in this research is the overlap that exists between systems engineering and project planning.

According to Fossnes and Forsberg (2006) from INCOSE, this overlap is referred to the management of risks and opportunities. Figure 1.1 provides a scope of the research areas in this dissertation. The focus of this research is in the conceptual design stage of a product's life-cycle. There are two key contributors to the design decision-making process: programmatic and strategic factors. Programmatic factors are typically associated with technical, cost or schedule changes that arise internally throughout the development process and strategic factors are external effects that impact the design decisions. These two areas will be explored further throughout this chapter.

Most managerial activities in engineering design that deal with problem-solving, strategic planning, and resource allocation, contain one or more components of the decision-making process. Simon (1960) categorizes this process into three phases: Intelligence, Design and Choice. Current decision-making theories seek to understand the real-life context in which designers make decisions but often cannot make a rational case for the design choices made by the designers. Few entities know how to perform a synthesis of these analyses. There often exists a disconnect between decision makers at the engineering design level and managers

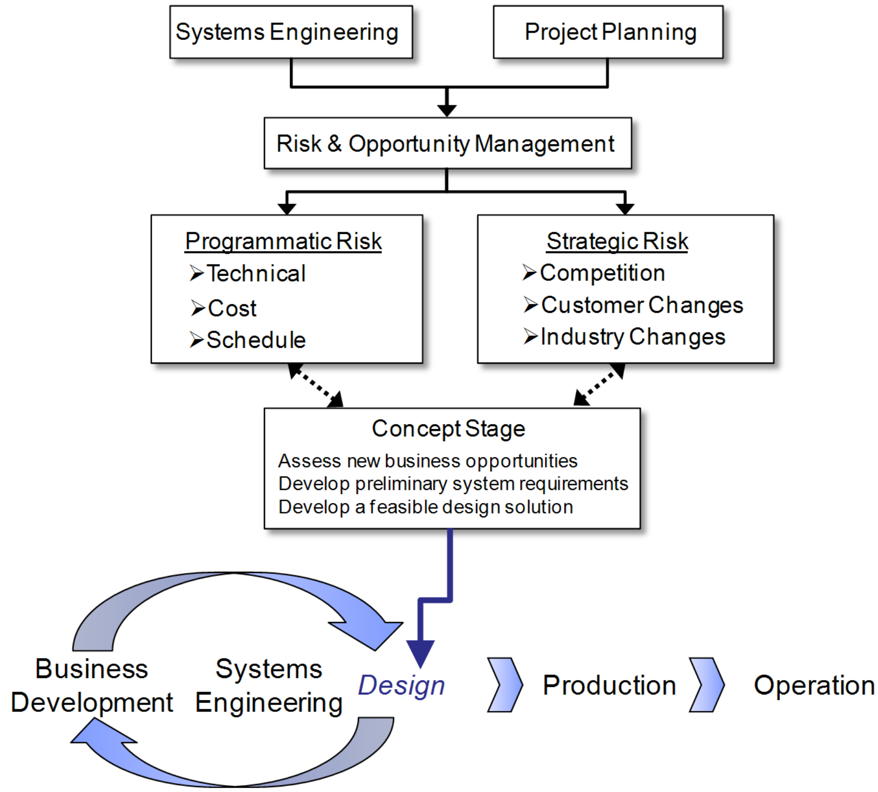

Figure 1.1: Product Life-Cycle Stages (Modified from Fossnes and Forsberg (2006))

at higher levels. This often results in failed promises to customers and the accumulation of financial penalties. Decision-makers at all levels also have to distinguish between quantitative and qualitative factors such as cost, performance, and customer satisfaction. At the technical level, designers tend to make more quantitative decisions whereas managerial decisions usually involve more qualitative factors. A framework is needed that enables decision makers at all levels to understand and explain the implications of choosing one design over another and improve the transparency of information between conceptual design engineers and project management.

Conceptual engineers designing a commercial jetliner have to incorporate not only the various elements and disciplines that comprise the aircraft but must also account for airports and other supporting infrastructure as well as the larger market picture and global economy. Each of these factors play an important role in the success of the commercial jet and its operating airline. However, not all design decisions for example, associated with an engine (subsystem-level) are made in unison with decisions about entering the aviation market (system of system-level). Furthermore, there often exists a disconnect between the those making decisions at one level and those at another level of the system.

An important aspect of complex systems design is that both technical and management processes must be closely interlinked (Souder, 1980; Tesar et al., 2003; Mackenzie et al., 2004). More importantly however, is the fact that the decisions take place over long, intermediate, and short-term planning horizons. Long-term decisions will generally address *strategy*, by considering such questions as when and which market to invest into, what risk is involved, how to market the system, who to partner with, where to produce it, etc. Intermediate-range decisions are *tactical* in that they address more directly the product with a more in-depth study of the financial implications at a more detailed level. These tactical decisions must be made within the boundaries established by the strategic long-term decisions. Finally, short-range decisions involve fewer decision-makers that have *local* control over a particular component or an analysis operation. Therefore, integrating these activities, with scope or time elements usually complicates the design process. In the aerospace systems design process, these different decisions take place but, like most businesses, are often made in isolation of each other. Furthermore, engineering design teams focus on the lower-level, technical aspects and very little attention is given to the broader strategic decisions. Several managerial decision-making methods exist that cope with some of these challenges (Souder, 1980). Most of the existing advanced design methods in academia today are directed towards improving both the quantitative and qualitative decisions in technical disciplines where results can be obtained in a relatively short time period.

The underlying ideas behind the proposed research focus primarily on the harmonization between systems integration in conceptual design and the strategic risks that exist when introducing a new commercial vehicle at the market level. The *risk and opportunity management* domain shown in Figure 1.1 identifies the various factors that contribute to the uncertainty present throughout the life-cycle of a system. The concept of strategic risk and its relationship with market competition are the motivating themes in this research and are expanded further in the subsequent sections.

1.3 Beyond Systems Engineering

An indicator of success in engineering design is the ability to practice it within a broader context. This means generating designs with all disciplines in mind and systems engineering is at the forefront of this process. As defined by Fossnes and Forsberg (2006):

> *"**Systems Engineering** is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect."*

The systems engineering community approaches each problem with a process to interface with external system elements such as the stakeholders, customers, markets, maintenance, manufacturing, production management, etc. One author illustrates this perspective in Figure 1.2 as the business case for any engineering problem.

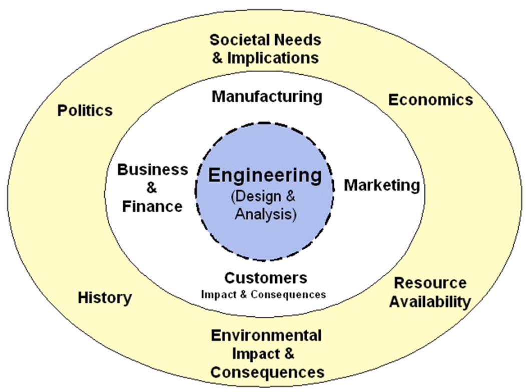

Figure 1.2: The "Design Onion" (McMasters, 2002)

At the core of any engineering problem is its design and analysis process. This process consist of three main phases; conceptual, preliminary and detailed design (Anderson, 1999; Raymer, 1999). The conceptual phase can differ slightly but typically consists of creating a fuzzy representation of the overall shape, size, weight and performance of the product. The activities at this stage involve evaluating the overall performance and feasibility of the design via numerous iterations between customer requirements and system configuration parameters. The decision-maker then determines whether a satisfactory performance is met by all parameters and initial requirements are met. The design(s) is then considered feasible enough for further analysis at which point it enters the preliminary design phase.

Preliminary design or embodiment design may include more thorough performance analyses and component configurations. At this stage, comprehensive aerodynamics and structural performance calculations are made with appropriate drawings indicating specific component placement (Raymer, 1999). A preliminary selection of materials and manufacturing processes are established and tolerances and dimensions are provided. The final stage is the detailed design phase where detailed drawings and specifications are made for the product.

The traditional approach to design was driven primarily through performance measures. Without the advantages of modern computer capabilities to facilitate decision-making other key objectives like cost, maintainability and so on were dealt with in the latter stages of the design process. Limited information about the impact of the surrounding environment such as the market and competing firms meant that decision-makers relied on intuition and heuristics to make design decisions.

In the aerospace industry, studies by Monteleone (2001) confirm that the impact of factors like *customers* or *politics* has a significant impact on the design decision-making in the conceptual phases. Decisions within the non-technical areas are often deciding factors in determining the success of a program. The competition between Boeing and Airbus is a good example of where strategic decision-making plays a key role in developing design concepts.

Boeing initiated the Sonic Cruiser concept in the late 1990's as a response to Airbus' A380, claiming rapid point to point connections was the key to future travel. However, in part because of the political and financial impacts on the airline industry from the September 11, 2001 events, customers then favored lower operating costs over a marginal increase in speed. This forced Boeing to end the Sonic Cruiser program and leverage its technologies to develop the new B787. This new program presented a serious threat to Airbus' existing A330 with its lower operating cost. Although Airbus initially rejected these claims, increasing customer pressure forced Airbus to propose a simple derivative of the A330 dubbed the A330-200lite with improved aerodynamics and engines. However, with continuing dissatisfaction from the airlines, Airbus was forced to formally launch a four billion dollar investment into the development of a new replacement, the A350. It became the B777-200ER and B787-9's biggest competitor. But airlines noticed that the A350's design was not fully developed and did not provide significant improvements over its competitors. The wing design was somewhat outdated and the fuselage remained the same as the A330 and A340. Airlines shifted towards the B787 and those that remained on-board pressured Airbus to completely revamp the design and create an all new wide-body. In response, Airbus unveiled the A350XWB family with a new fuselage, wider than the 787 in addition to other improvements but with a delay in entry into service (Flight International, 2006). Both companies have invested billions of dollars into various programs in order to satisfy airlines and gain market share. This example illustrates how technical design decisions in conceptual design are only as successful as those that deal with the larger strategic problem.

The challenge is to understand why some research and development (R&D) projects fail while also predicting how others succeed in the market. According to Balachandra and Friar (1997), in the early 1990's almost 90% of approximately 16000 new products introduced did not meet their business objectives. The key to a successful system in the market is to achieve a balance between the business aspect, the budget aspect and the technical aspect. The mindset of systems engineers is develop a technical solution that follows the business case and meets funding constraints. Systems engineering plays a role in the business development as much as in the design itself. INCOSE highlights the main components of a business life cycle in Figure 1.3. The INCOSE handbook defines the concept stage of systems engineering (Fossnes and Forsberg, 2006):

> *"The concept stage of systems engineering is executed to assess new business opportunities and to develop preliminary system requirements and a feasible design solution."*

In many current design approaches, like propulsion design, decision drivers are primarily based on performance (technical) metrics. Preliminary design engineers in engine manufacturing companies are turning towards academia to help develop methods or techniques that will help them drive decisions with customer value and business return early in product development. The challenge is to find ways to incorporate the business case into the

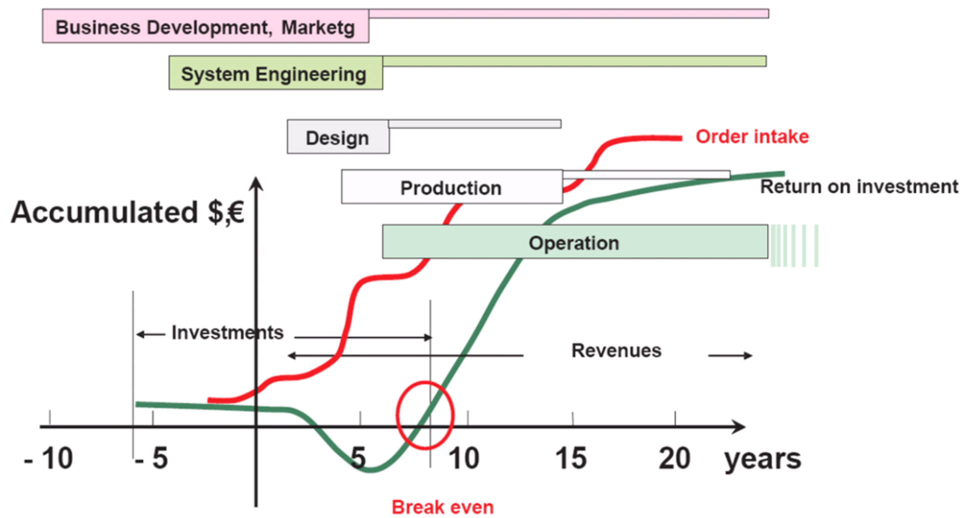

Figure 1.3: Generic Business Life Cycle (Fossnes and Forsberg, 2006)

different technical processes that take place in conceptual design and is an underlying focus of this research. An understanding of the technical design process is necessary in order to determine where to incorporate business-centric variables. This can be formally written as:

Observation 1: Financially successful research and development programs in aerospace engineering are a product of a comprehensive understanding of the business case and its relationship with the technical design environment. The engineering design process could benefit from methods that analyze market uncertainties and their impact on design decisions.

Designing aerospace systems with useful market knowledge and information is vital to making accurate decisions throughout the R&D phase. Decision-making in project selection is therefore an important element early in design. Fortunately, progress in the decision-making fields has enabled engineers to become better equipped at making complex choices.

Expanding the engineering design space to include the analysis of market uncertainties in systems engineering has been a primary objective throughout the investigations in this research. As the technological and competitive landscape are evolving, the firm's strategic decisions are precisely what will determine its competitive success and market survival. The problem lies in the fact that managers have had to make decisions in the absence of structured, quantitative analysis, relying primarily on intuition and experience. A need has emerged in conceptual design to study the importance of the market on engine selection and in order to limit the scope of this research one of the areas of interest for further review is the study of market uncertainties in systems engineering. At the end of this chapter, a compilation of observations, objectives and research areas will be presented.

1.4 Decision-Making in Design

The importance of decision-making in systems design cannot be emphasized enough. Systems design problems generally deal with both physical and organizational parameters in a multi-dimensional setting. Product selection is made from a large set of alternatives and must be made by considering many diverse factors. However, as expressed earlier, both managers and engineers traditionally use one-dimensional tools to make design decisions. Engineering choices are often made in a disciplinary fashion, which are driven by specific areas of expertise, like aerodynamics, structures, propulsion, etc. Managerial decision are likewise independent of the engineering capabilities, and focus primarily on the business aspect of the problem. As a result, product design is mismanaged and subsequent failures occur. The bottom line is that decision-making at any level in the design process hierarchy must be well structured so choices can be made as accurately as possible. Suh (1990) recognizes the role of decision-making in design by stating:

> *"In order to obtain better performance, both engineering and management structures require fundamental, correct principles and methodologies to guide decision making in design..."*

There is extensive literature that addresses the field of decision-making. Chen and Lewis (1998); Lewis et al. (2001) acknowledge that poor decision-making cannot be solely as a result of poor information that the designer held at the time of the decision. Instead, Hazelrigg (2003) contends that "*faulty decision methods are also likely causes of bad engineering design decisions"*. He claims that although many engineers have developed numerous decision tools for selection in design, these tools do not necessarily contain the formalisms of decision theory. The science of decision theory is based on a mathematical framework that has been employed in applied economics, operations research and a wide variety of other fields(Pratt et al., 2008; Clemen, 1997).

There does exist a decision-making hierarchy in systems design problems that involves the overall business objective of the organization. Strategic management is the approach taken to link the vision, resources, environmental circumstances and core objectives together to outline an overall corporate strategy. This topic will be reviewed further in the strategic risk section in this chapter. What is important about business decision-making here is that organizations are generally not highly centralized structures where important decisions are made at the center. Instead, organizations decentralize decisions.

> *"Matters of fact can be determined wherever the most skill and information is located to determine them, and they can then be communicated to 'collecting points' where all the facts relevant to an issue can be put together and a decision reached"* (Simon, 1996).

Most systems design organizations follow a similar decentralized decision-making structure. The organization is generally subdivided into specialized groups that perform specific functions such as: investment and funding decisions, administrative decisions, strategic planning, marketing decisions, engineering design decisions, etc. The fact that the decision-making is decentralized does not mean that the decisions for each group are one-dimensional. For this reason it is important to search for selection techniques that allow for the inclusion of both physical (technical) and business (non-technical) parameters. The organization of a engineering enterprise can be defined in a functional manner to facilitate the understanding of design and product development. Dieter (2000) shows how the Department of Defense (DOD), a major sponsor of R&D projects, classifies engineering functions in Figure 1.4.

As stated in the previous section, there are many disciplines beyond the technical that need to be brought back into the decision-making problem early in the process. Decisions become hierarchical such that some decisions may have a short term impact vs some that may have be long-term with potentially more significant consequences. Decision-making in systems design is a *process*, not an event. This evolutionary process almost always involves iteration. In many organizations, there exists top level managers, mid level managers, supervisory managers, technicians and other experts, each making an independent contribution to the analysis of a complex systems decision problem.

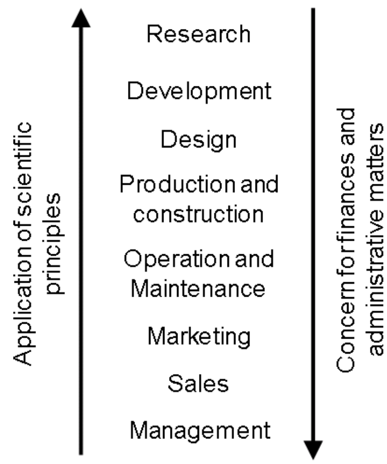

Figure 1.4: Spectrum of engineering functions (Dieter, 2000).

An example of hierarchical decision-making that currently exists in system design problems is illustrated in Figure 1.5. The horizontal axis describes the number of decision-makers

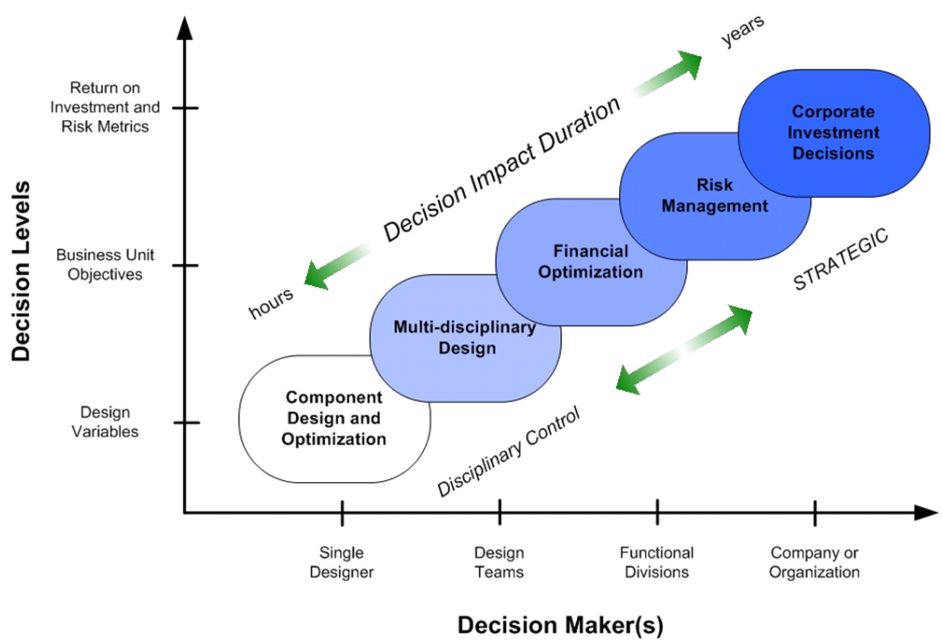

Figure 1.5: Systems Decision-Making Hierarchy

and the vertical axis represents the level of detail that a specific decision corresponds to. The third axis is the arrow which describes the time element associated with the decisions. This time third axis can also represent the degree of freedom associated with decisions. At high levels in the hierarchy, the decisions will generally affect the system as a whole thereby having greater freedom for change.

This section has introduced the significance of good decision-making early in the design process and thus the need for more adequate information about the problem. Skinner (1999) reminds designers in his *"ten principles of good-decision-making"* that they must *"understand the business situation and the external factors influencing the problem"*, which is a primary objective embedded in this dissertation.

1.5 An Aerospace Market Overview

With the emergence of new markets around the world in recent years the aerospace industry is rapidly adapting to the accompanying increase in travel demand. Large-scale aircraft manufacturers such as Boeing and Airbus have taken advantage of growing economies in China and India to expand their production facilities and establish business roots. Boeing Commercial Market Outlook (2008) forecasts air travel demand to grow to 29,400 airplanes in all size categories by 2027. The Asia-Pacific region will be at the forefront of this growth with a predicted demand of 9,160 aircraft. These are impressive figures that indicate significant aviation growth in the future and which will require more efficient aircraft to cover expanse regions of the Earth.

Alongside the airframe manufacturers engine companies are also expecting an increased demand over the next 20 years. Both General Electric (GE) and Rolls-Royce (RR) are competing in the B787 and A350-XWB markets, with the GEnx and Trent1000/1700 respectively. As Pratt and Whitney (PW) begins development of its new Geared TurboFan (GTF), both GE and RR are actively pursuing next-generation engines of their own. Airbus recently announced that it would be willing to enter the GTF competition against Bombardier's CSeries but saying that *"it would probably take the best part of two to two-and-a-half years to develop a GTF-powered A320"* (Flight International, 2008). Although engine manufacturers have similar looking engines their internal architectural designs and capabilities differ so they can differentiate themselves in the market. Airlines have several engine options available to chose from for a particular aircraft model. Figure 1.6 illustrates the two top airframe and three top engine manufacturers in the commercial aviation industry. The figure shows each aircraft model with two or three engine options and the six engine manufacturers are listed at the bottom. Deciding to produce an engine for a particular aircraft model requires extensive conceptual analysis.

Figure 1.6: Competitive Propulsion Applications in Commercial Aviation (Airbus Industrie, 2008; Boeing Commercial Airplanes, 2008)

The competition in the engine markets is not as clear-cut as it may seem. The trend in the past decade or so has been for manufacturers to form joint ventures and partnerships for risk-sharing purposes. Companies are having to *"listen more to customers, work with suppliers, and establish strategic partnerships- even with competitors"* (Brandenburger and Nalebuff, 1996). In order to formulate better business strategies companies must understand the inter-dependencies that exist between players, as well as the multiple roles they may play.

Understanding the aircraft requirements is only a small part of the conceptual design problem. Many more non-technical variables affect the decision-making in conceptual design. These are influenced by the many participants in the market. From the perspective of an engine manufacturer, the aviation industry's participants are categorized as competitors, complementors, customers and/or suppliers. This industry can be envisioned through the Value Net created by Brandenburger and Nalebuff (1996) and illustrated in Figure 1.7.

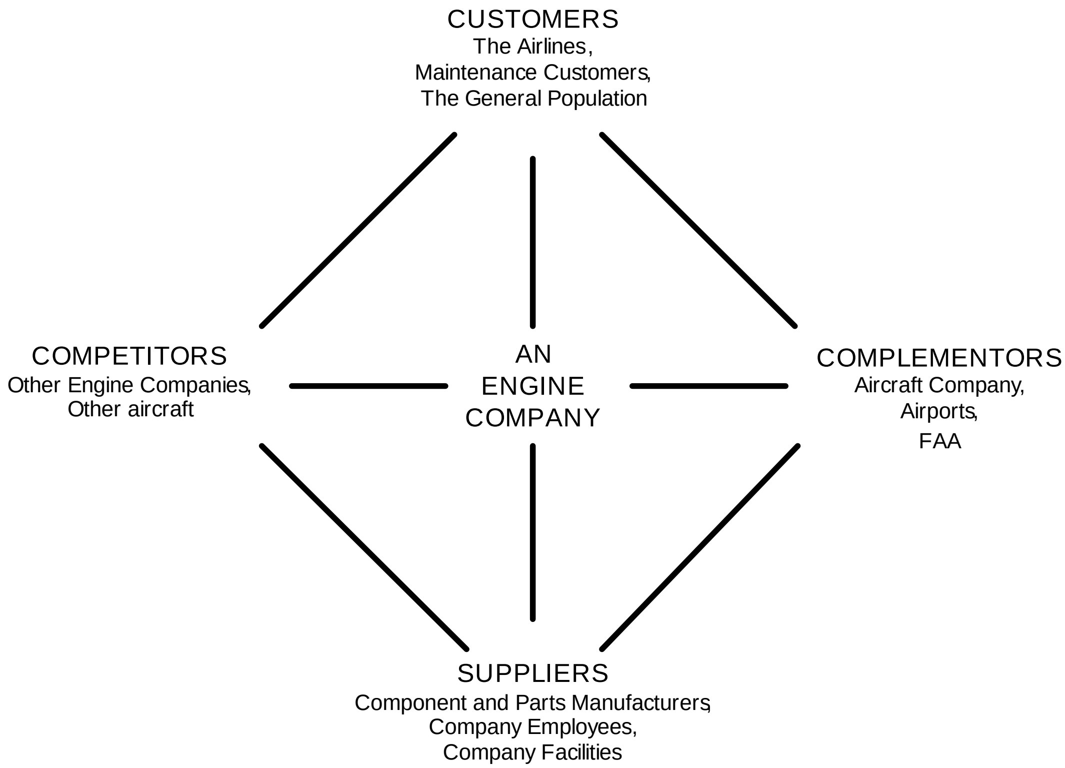

Figure 1.7: The Value Net for an Engine Company (Brandenburger and Nalebuff, 1996)

Competition in the engine industry has significant leverage on the future sales for engine manufacturers. Monteleone (2001) represents a well-established aviation consulting firm that points out that *"engine manufacturers want market share and will do pretty much anything to get on the wing and make up their costs on the back end".*

Every company has an incentive to maximize the return on investment for their stakeholders. This objective translates to making sure that the product does well in the market. A conceptual design author makes the case for analyzing competition (Mattingly et al., 2002):

> *"The designer will also experience a natural curiosity to find out what the other engine companies are proposing. This curiosity can be satisfied by a number of legitimate means, notably the free press, but each revelation will only make the designer wonder why the competition is doing it differently and cause his or her management to ask the same question."*

Since the core engine design is locked in early in the design process, the ability to predict how your product will do against the competition once it enters the market is vital so that the design can be optimized for potential market consequences. Especially since choosing the *right* engine from the airline's perspective is not straightforward. There are many financial incentives and intangible criteria involved in the negotiation process with engine manufacturers. However, a significant part of the negotiation relies on performance objectives instead of financial or economic criteria. Therefore, integrating the customer and performance metrics collectively into a process provides a better understanding of how the engine will perform in a market.

1.6 Competitive Designs

Engineering systems design is described as a process where the key to successful decision-making is good information and the knowledge to use it. There are various formal methods within the realms of decision theory and multi-disciplinary design that are used to obtain such information and use it to examine decision-making problems. This type of engineering design can be viewed as a "game against nature" where designers seek to maximize the utility of a system. Nature represents a limitation or constraint on the design and generates uncertainties on the outcomes. In the design of defense systems such as military aircraft this type of decision-making philosophy is applicable. However, in other design problems, systems design is not only limited by 'nature' but also by competing designs. The commercial aviation industry is a prime example where the element of competition plays a crucial role. Airframe manufacturers are continuously competing over price, speed, range, comfort, etc. in a market full of exigent customers. The decision-making environment under conditions of competition is the underlying theme of this research.

A common design objective can be expressed in the form of a utility function that allows designers to rank alternatives. There is however, no utility function that represents nature. Nature presents uncertainties in many forms (storms, earthquakes, etc) that may influence the operation, reliability, safety, and lifetime of engineering systems. The one thing nature does *not* do is produce competitive designs. Competition occurs with people or entities that have preferences or utilities that are often in conflict with one another. A company that designs a product to compete against other companies is consciously making design decisions that affect its competition. This type of competitive situation is defined as a game by Hazelrigg (1996):

> *"A game is any activity that involves more than one individual, where the actions of each individual in the game affects others who are also in the game."*

The research proposed in this dissertation creates a structured process for conceptual designers in complex systems engineering problems that analyzes (uncertain) competitor information for the purpose of generating actionable design strategies. This requires a more rigorous definition of the meaning of *competition* in systems engineering. Merriam-Webster (2003) defines competition as:

> *"The effort of two or more parties acting independently to secure the business of a third party by offering the most favorable terms."*

This notion of competition can be defined similarly in the context of propulsion systems design as:

> The effort of two or more *design alternatives* acting independently to secure *the business* of a *marke*t by offering the most favorable *terms*.

Where:

- **Design alternative*s*:** Engine architecture designs (note: these designs may represent two or more companies)
- **The business:** Commercial aviation
- **Market**: Airlines (Customers)
- **Terms**: Robust aircraft/engine package for airline's intended purpose

Hernandez et al. (2000) and Marston (2001) show how a competitive game can be described as an optimization problem where there exists two or more objectives or utility functions, and corresponding to each utility function, a separate set of control variables. Systems design problems can be decomposed into complex games (Fernandez et al., 2005). Multi-disciplinary problems are modeled as games where the players represent different disciplines like aerodynamics, weights, propulsion, etc (Vincent, 1983; Chen and Lewis, 1998; Ferguson and Lewis, 2004; Lewis and Mistree, 1996). But multi-disciplinary design problems ultimately have one common goal and that is to produce a design that minimizes or maximizes a global objective function. The competition is now external to the company and the players are the companies themselves. The environment in which they compete is the market. One of the underlying interests in this research is to examine how the competition in the market impacts the design choices in the technical disciplines of design problems.

In propulsion systems design, there exists many disciplines that may have conflicting objectives. Design areas like customer value, manufacturing cost, and business financial return directly influence how an engine should be designed. Engines may contain technologies that make it have the best thrust and lowest weight but how successful is that engine if its manufacturing and maintenance costs are too high which means the return on investment and customer value are too low. What if a competing engine placed more emphasis on customer value and strategized appropriately for the market? More than likely that company would fare better in market share. So how is the strategic game won for propulsion systems? There is extensive research in academia that analyzes the impact of technologies and improves the technical potential of engines. This is a game against 'nature' that produces incremental gains in design performance. There is very little impact on the success of a design in improving component efficiency by one point or less. With only a few revolutionary technological game-changers on the horizon the strategic game can no longer rely solely on technology investment. Early in the design process, there are key design decisions that fix the the design. These decision are in fact strategic because they impact every discipline at some point in the future. Examples of strategic design options are consist of, but are not exclusive to:

- The selection of a 'correct' propulsion architecture:
  - 1-stage high pressure turbine vs. 2-stage high pressure turbine
  - 2-spool vs. 3-spool vs. geared fan
- Setting the design point for maximum flexibility:
  - Airframe family evolution: extended range, increased take-off gross weight, etc.

– New family designs

These strategic options in conceptual design are considered product development decisions. As noted earlier, an evolving marketplace has meant that conceptual designers are going beyond their engineering capabilities to address non-technical characteristics of innovative product development design decisions. Studies by Ali (1994); Ali et al. (1993); Ettlie (1997); Loury (1979); Mansfield and Wagner (1975); Rosenberg (1990) in the operations management and product development fields have shown that competition is a key factor to the innovation process. These observations culminate into the following:

Observation 2: Customer requirements and the intensity of rivalry between firms influence the engine architecture selection process. Selection mechanisms capable of evaluating both of these factors simultaneously are needed for increased selection confidence at the conceptual design level.

We are essentially attempting to improve the efficiency in designing new innovative products by addressing competition from an engineering perspective and managerial mindset. This leads to a second area of research that further bounds the scope of this dissertation and that is to investigate how competitive analysis facilitates decision-making in conceptual design.

1.7 Strategic Risk in Aerospace Design

An article from the The Wall Street Journal (1988) describes the competition between Pratt & Whitney (PW) and General Electric (GE) in the early and mid 1980s and their strategic choices in jet engine design. After losing a decade long market lead to GE in the mid 1980s, PW invested $1 billion in manufacturing a new, mid-size engine to power the new Boeing 757. GE instead chose to focus on improving its engines for the successful 747. PW's decision to build a brand new engine was a much riskier yet potentially more lucrative approach to GE's decision to upgrade their existing engine line. These are two distinct product selection strategies that had a major impact on the each firm's return on investment and ultimately their survival in the business. There is a strategic risk associated with pursuing different types of product development projects and competitive positioning is a key factor. Ali (1994) reaffirms the importance of the competitive effect on product development strategy.

In particular, he studies how anticipated competitive behavior may affect other firm's choice in product selection.

The focus of this dissertation is competition and how to analyze and interpret it within the realms of engineering design. Design choices made based on these analyses are going to have an associated level of risk. The risk involved in developing and pioneering new innovative engines may inhibit firms from committing resources to their research and development. Identifying, mapping and mitigating this risk is part of the risk management process that is of interest in this research. There are many well established risk management procedures that are noteworthy. Fossnes and Forsberg (2006) provides a risk and opportunity management process that studies the risk and opportunities present in the life cycle of systems. The National Aeronautics and Space Administration (2004) (NASA) branch of the United States government also has a well-documented risk management plan that details procedures to identify, analyze, track and mitigate risks.

The risk management framework drawn from the Institute of Risk Management (IRM), the Association of Insurance and Risk Managers (AIRMIC), and the National Forum for Risk Management in the United Kingdom provides an appropriate start to identifying strategic risks. The framework is presented in Figure 1.8.

The framework identifies four main contributors to strategic risk. This research seeks to evaluate primarily competition and customer changes as the main risk factors associated with new product development. The choice between an new or modified product is one of great strategic importance to conceptual designers. In addition, studies by Ali et al. (1993) show that the impact of entering the market with either product before or after the competition can be a highly rewarding investment or a very risky strategy. There are certain firm characteristics, like the choice of new or modified product choices as well as market entry timing that influence the strategy for product development early in design. These aspects of product development exist in the development of aircraft engines are are central to the investigation in this research. A third and final observation can be summarized as:

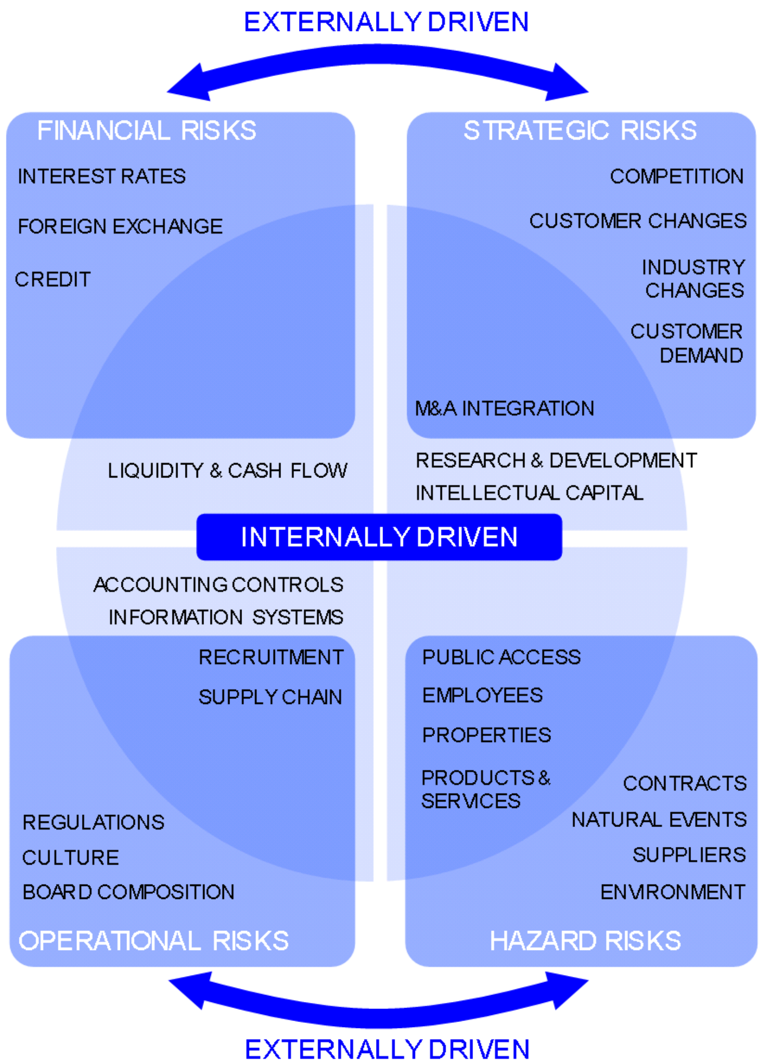

Figure 1.8: A Risk Management Framework (The Institute of Risk Management, 2002)

Observation 3: In aerospace design, the probability of economic success of engine development strategies is dependent on market entry timing and development duration in addition to the performance of the engine design.

In order for a company to better mitigate risk in a dynamic global market and to be economically successful there is a need for innovative methods to assist propulsion system decision-makers as they account for these larger strategic impacts.

Two main deficiencies have been identified in most systems engineering conceptual design problems. The first is that conceptual design decision-making at the engineering level is typically based on performance and affordability metrics alone. This results in designs that do not have sufficient competitive or strategic leverage. Secondly, the current system architecture down-selection process in conceptual design is conducted with a reduced amount of knowledge and information about competitive and market uncertainty and their relationship with the technical parameters. This problem can be summed up as an ongoing disconnect of information between the design engineers at the technical level and the upper-level management. A primary goal in this research is to adequately introduce the notion of strategic decision-making early in the design process. Throughout this dissertation, *strategic design* is defined as an approach to efficiently develop new designs by forecasting changes or fluctuations in technical capabilities, customer requirements and market competition. This involves a systematic execution of methods and procedures for performance and affordability implementation, technology infusion, and competitive hedging.

Design decision-making must therefore include some element of competitive analysis of the manner in which conceptual designs are influenced by market forces. This may involve a broader perspective of design for growth within a product family and ways to strategically position the family for maximal investment return in the competitive markets of today and tomorrow.

The third and final research area of interest is the selection of project development strategies in competitive environments. The review of literature in this field will limit the scope of the investigations to the study of selection strategies based on competitive effects.

1.8 Dissertation Organization

The previous sections introduced the main areas of study that are covered in this research. They also highlighted possible analyses that were lacking in current systems design processes. The deficiencies of current engineering design methods, coupled with the promise of strategic design, is the impetus for this work. The observations made provide guidance for the development of formal objectives that this research aims to accomplish.

> **Objective 1:** Expand the engineering technical design space to evaluate the market performance of large-scale aerospace systems.

Objective 2: Introduce mechanisms that quantitatively model competitive scenarios and their impact on the resource allocation for a portfolio of engine architectures.

Objective 3: Establish a framework for down-selecting engine strategies that accounts for uncertain development periods and that benchmarks potential design performance against the competition.

The purpose of the first objective is to create a foundation within the conceptual design process that enables engineers to introduce economic models and their attributes into the parametric design space of aerospace systems. Particularly in the design of commercial systems, revenue and cost models are essential to evaluating economic success. A unified framework that allows engineers to map performance and economic requirements concurrently within a single design space is also beneficial from a managerial perspective. The concept of market performance is meant to focus on the economic success of a particular design within a particular market segment. Throughout this research, this performance will be evaluated in terms of market share and its subsequent value to the manufacturer. The task of expanding the existing technical design space to one that incorporates market attributes is no easy task. The first focus area for this research will be to investigate which elements are needed to create an environment that is capable of modeling both technical and economic metrics concurrently.

The second objective builds on the first by taking the environment one step further to analyze the dynamics of competition between two or more entities. The goal here is to investigate methods and techniques that can quantitatively measure competitive scenarios. Of particular interest are techniques that provide competitive response strategies to facilitate the selection of engine architectures. For this reason, the second focus area of this research is dedicated to investigating competitive methods and techniques. Finally, the third objective is meant to guide the selection process of engine architectures. When making engine architecture choices the number of decision criteria is often overwhelming. The importance of each criteria can also has a significant impact on the choice of design architecture. This is a foreseeable challenge and thus a third focus area is to investigate which criteria are most important to a manufacturer when selecting an engine architecture design.

These objectives provide the direction that is necessary to answer the global research question of this research:

> *How can aerospace architecture solutions be generated in the context of uncertain competitive scenarios and be strategically explored for optimal selection?*

The traditional design process as applied to aircraft engine design does not have the means to address the issue of strategic decision making early in the conceptual phases. It is now possible to look into answering questions such as what path(s) overall will maximize return on investment based on market changes or customer makeup? This dissertation provides an introduction to and examination of the strategic decision making aspects of commercial engine selection and design. Additionally, since the engine design/selection problem involves making key economic decisions in a competitive environment, it is reasonable to introduce some aspects of game theory within the decision analysis.

The development of a methodology for analyzing market competition in the conceptual design phases of design is presented in this dissertation. The motivation and problem definition sections served to provide a frame of reference and to delineate the scope of the research. Chapter 2 provides a background of the relevant methods and techniques that characterize the state-of-art. Innovative competitive analysis techniques are the subject of Chapter 3. The research questions and hypotheses are then formulated in Chapter 4 based on the literature review and competitive techniques. These questions and hypotheses guide the development of the methodology. Chapter 5 implements the methodology on a commercial engine selection problem as a proof-of-concept. The dissertation concludes in Chapter 6 with a revisitation of research objectives and recommendations for future work.

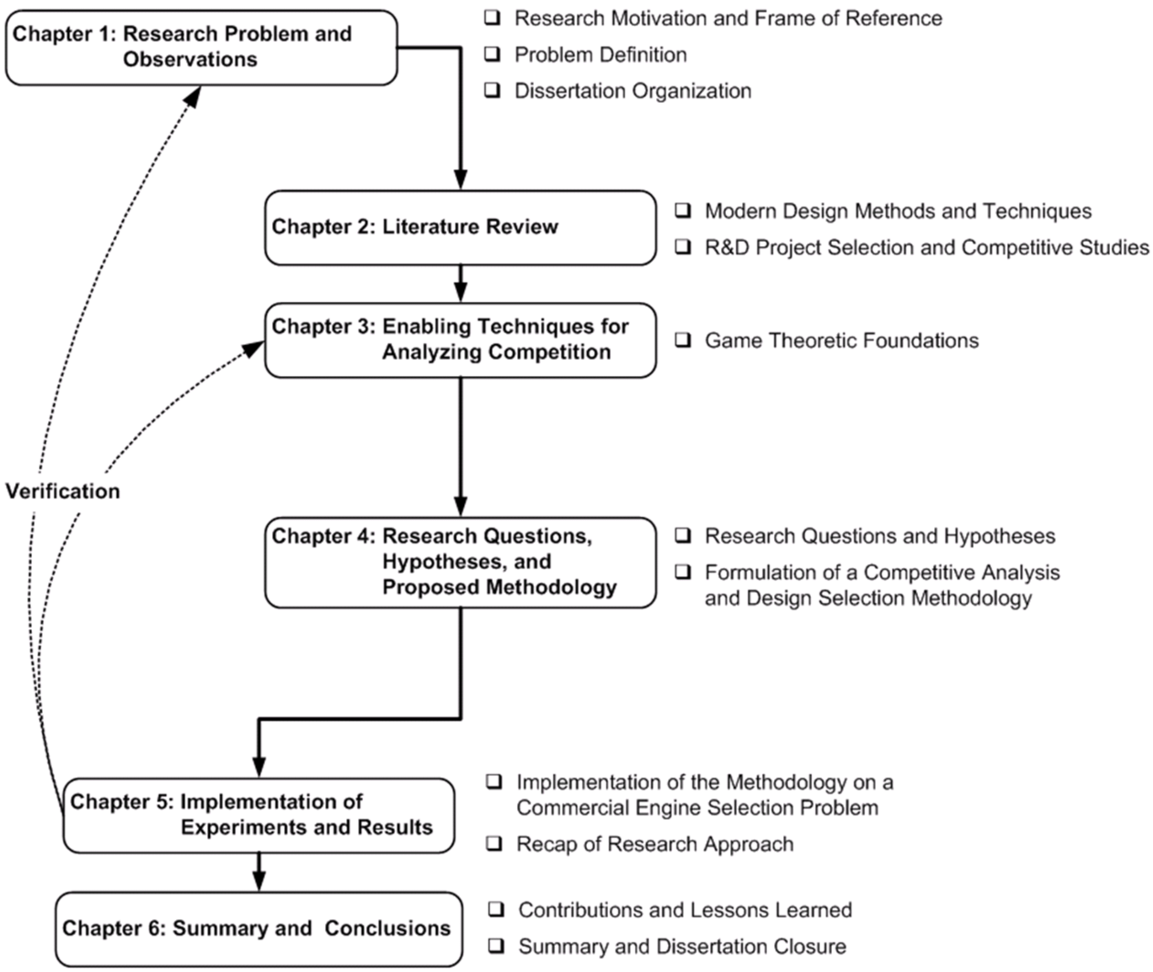

Figure 1.9: Dissertation Structure

Chapter II

LITERATURE REVIEW

The purpose of reviewing the literature is to survey existing methods, processes or techniques that address and help achieve some or all of the research objectives. Throughout this process it is possible to determine if and where there are gaps in the literature that are consistent with the top-level research objectives established in the previous chapter. Based on the information gathered in this review, existing gaps will be explored and bench-marked to determine where more advanced methods may be needed to enable the development of the proposed competitive analysis method.

There are five main sections to this chapter that are loosely organized to fit within the scheme set up by the three research focus areas described in the previous chapter. The first two sections introduce the field of aircraft engine design and provide a historical overview of commercial engine selection studies as well as recent challenges in the design process. A review of modern systems design methods is conducted and together with the strategic analysis and planning section addresses the first research area. The fourth section reviews the literature associated with project selection and primarily addresses the third research area. Finally, the fifth section reviews competitive methods and analytical approaches in both the business and engineering domains and bounds the scope of the second research area. The sixth section provides a summary and a set of criteria to help identify the strengths and weaknesses of the competitive techniques.

2.1 Aircraft Engine Design

The degree of complexity in engineering is driven by many diverse disciplines. There is an intricate process by which these disciplines interact to bring a product to fruition. Although Dieter (2000) claims *"there is no single universally acclaimed sequence of steps that leads to* *a workable design*", most designers agree that there are three definable phases of design: conceptual, embodiment (preliminary) and detailed design. Each is a decision making process that begins with a creative idea or concept, and ends with a realized product. A principal engineer in the propulsion industry, Halliwell (1998) states:

> *"The design and manufacture of a modern gas turbine engine is a manifestation of an intense and lengthy cooperative effort of communication, sharing, understanding, and ultimately of compromise between practitioners of all of the technical skills, and in today's world, of economics and marketing."*

After establishing the need for a new or modified engine, conceptual design usually begins with an account of the engine requirements. The general size, configuration, and performance of the engine are determined based on requirements set forth by an RFP or specified by market demand (Raymer, 1999). It is at this stage that designers determine if a potential engine will meet the customer requirements and if not, the customer may choose to relax or revisit the requirements. At the end of this phase, the engineer should have a workable design that has met key requirements, incorporated desired technologies, has gone through extensive design point studies and finally is both feasible and affordable to produce.The conceptual and embodiment design phases may often overlap depending on the definitions of each. Halliwell provides a straightforward view of the design process from concept to manufacture in Figure 2.1.

One of the first questions the engineer will ask himself is if the engine design will meet the the required specifications given by the requirements of the aircraft mission which, can be both technical and economic in nature. Following the mission profile requirement and aircraft characteristics that specify mission segment thrust requirements several engine configurations are proposed and the engineer will determine which *best* design meets the specifications. This will depend on how each candidate design performs in the cycle analysis where weight and performance calculations are made over the complete mission. Information from the thermodynamic design point studies and critical off-design performance is used to help choose a cycle as well as a preliminary layout of the turbomachinery. Another well established gas turbine engine design fra mework is proposed by (Mattingly et al., 2002) and is illustrated in Figure 2.2.

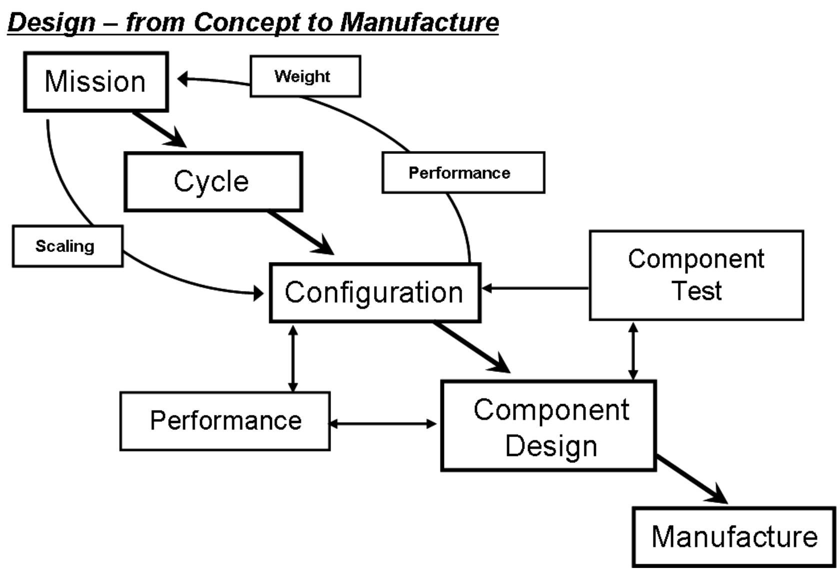

Figure 2.1: The Design Spectrum (Halliwell, 1998)

The cycle design point studies and configurations are usually determined by conducting parametric trade studies using preliminary estimates of the aerodynamics and weights of compressors, turbines, etc. An engine configuration is described as the layout of turbomachinery, specifying the number of spools or compressor/turbine stages. A number of design alternatives are evaluated to determine which concept is preferred. With the advent of computer power, analysis sophistication and fidelity has steadily increased to allow faster evaluation of alternative design concepts. The settings of the top-level design specifications define the conceptual baseline which becomes the configuration input for embodiment design, where the system is decomposed for more sophisticated analysis by discipline, subsystem, or component. At the detailed design phase, the subsystem components are fully designed and the system is manufactured for testing and development.

In the early stages of propulsion design, the engine architecture is synthesized at the system level based on performance and customer requirements and market opportunities. The primary objective of embodiment design is then to determine which of a number of alternative engine configurations to pursue further. Decision-making at this stage is critical since there is an irrevocable commitment of valuable resources and serious consequences of failure.

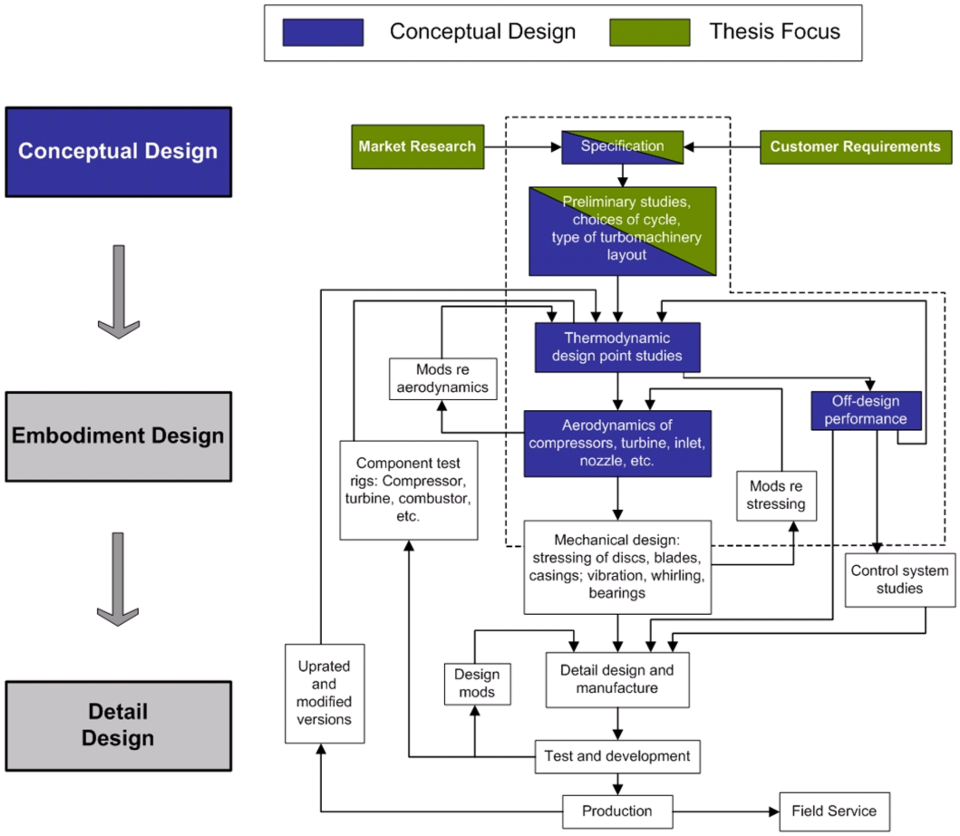

Figure 2.2: Gas Turbine Engine Design System (Mattingly et al., 2002)

Although the market research and customer requirements steps from Figure 2.2 are extensively researched in industry and academia, they are not addressed concurrently with the technical specialties. Instead, the engineering technical analyses (the core of the design process), have largely become the focus of the design process. Many project managers are reluctant to carry out strategic impact evaluations because they are deemed to be expensive, time consuming and technically complex, and because the findings can be politically complex, particularly if they are negative. Yet with improved computational power and advances in the multi-disciplinary design and optimization fields and other modeling techniques, engineers have been able to generate more sizable design spaces to perform more complex trade-offs and thus more rigorous architecture selection (Smith, 2003; Baker and Mavris, 2001; Mavris, Macsotai and Roth, 1998). A feedback link from the technical aspects of conceptual design to the market research and customer requirements in Figure 2.2 is therefore necessary to better match the technical potential of the company with its broader strategic goals. However, these techniques are only as good as the model fidelity of each analysis module. Therefore, in conjunction to improving the decision-making process in design, it is necessary that the quality of solutions be continuously upheld.

2.1.1 Architecture Selection Studies

In the conceptual design of commercial aircraft engines there is a constant pressure to continuously develop systems that meet the customer's requirements in the shortest time, with the lowest cost and with a high reliability. This is a challenging feat for systems engineers that have to also address the broader game problem that involves competitors, a political arena and economics. The difficulty in understanding how these factors influence each other is compounded by the fact that the rules of game keep changing. The airframe manufacturer will change the engine requirements, the customer will alter their requests, there is a reallocation of resources over time, etc. A necessary understanding of how factors evolve over time and more specifically how engineers can forecast this evolution is central to understanding and predicting competitive behavior. There is an increasing need for enabling processes or techniques that examines uncertain phenomena in conceptual design. Since most of the design is established early in the design process it is evident that having a means to understand how it will perform in the latter stages of the design process is of great importance to engineers.

There are several probabilistic methods that deal with design uncertainty, requirements uncertainty, economic uncertainty, etc (Mavris, Macsotai and Roth, 1998; Mavris and Roth, 2001; Rothwell and Gardiner, 1988; Kirby and Mavris, 1999). Whether it is aircraft mission changes or changes in emissions and noise regulations, there are emerging design methods that allow decision makers to select the most robust or flexible design to all these uncontrollable effects of the future (Baker, 2002; Mavris and Briceno, 2003, 2005; Kirby, 2001; Mavris and Roth, 2001). Probabilistic methods are commonly employed to understand uncertain effects in design. Figure 2.3 illustrates some uncertain characteristics associated with engine design.

The points illustrated in this Figure represent specific engines and their associated thrust

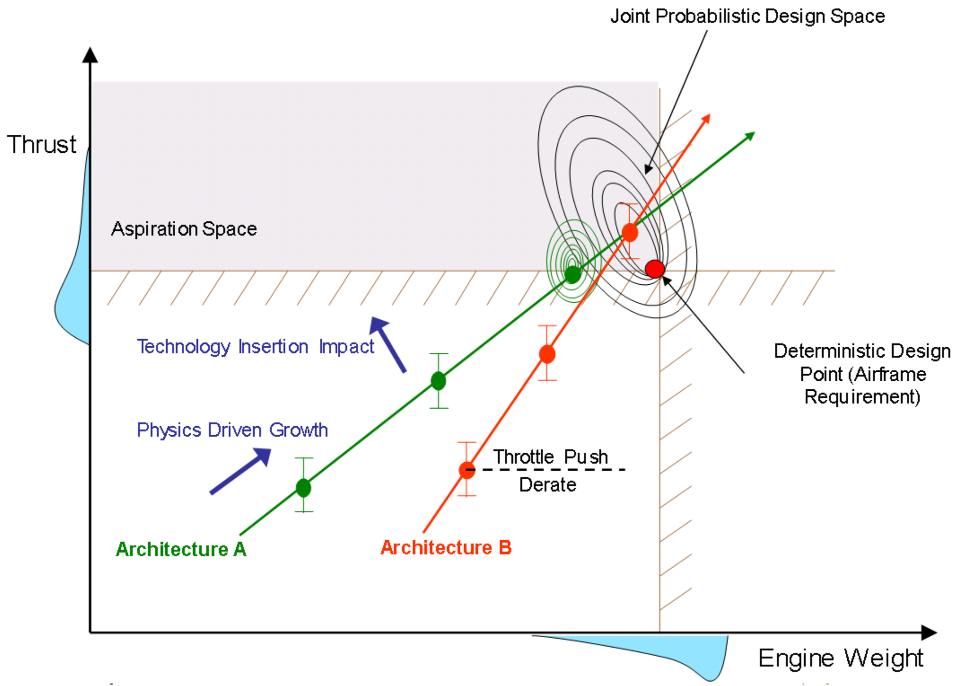

Figure 2.3: Impact of Internal and External Uncertainties on Core Engine Sizing and Architecture Selection

ranges. The two notional architectures represent two engine "cores" to which changes can be made to create derivative engines. Although the engine design space occupies many dimensions, for visualization purposes two dimensions have been selected and shown here. Two types of engine sizing trends are shown. The first growth trend is physics-driven, by which an engine can be made to produce more thrust at the expense of increased weight. The other growth trend is technology-driven. The exact position of an engine in the space can be described as a probability distribution depicted as solid density contours centered around the nominal engine design point. It is possible to see that one engine from both architectures shown may or may not satisfy the requirements. If it does not a newly developed engine design will be required. The design process might involve the modification of an existing engine in architecture A, or if this is not possible, the creation of a new engine. The question of which path is best now arises and represents the engineering view of the engine market problem.

The likelihood of a particular engine meeting the airframe design requirements can be determined by the intersection of two joint probability distributions. One that describes the airframe requirements uncertainty and the other that represents the engine design uncertainty. Mavris and Briceno (2003) demonstrate a measure of design *success* that can be obtained by these probability intersections. The analysis of uncertainty in engine design, discussed in the preceding section, does not account for future engine design considerations. It considers only the impact of uncertainty on a single requirement point without considering the associated uncertainty of evolving requirements. In order to take maximum advantage of emerging markets, designers must be prepared to strategically position their core design relative to their competition and design along the lines of a product family instead of a single application.

The complexities of modeling the various forms of uncertainty associated with requirements within a competitive business environment has been quite challenging for the propulsion community. However, new emerging techniques within the fields of complexity science, probabilistic analysis and game theory has enabled engineers to help solve these problems.Mavris and Roth (2001) developed a vision that brings together new ideas and theories to help advance the development of new methods within these fields. This vision is illustrated in Figure 2.4.

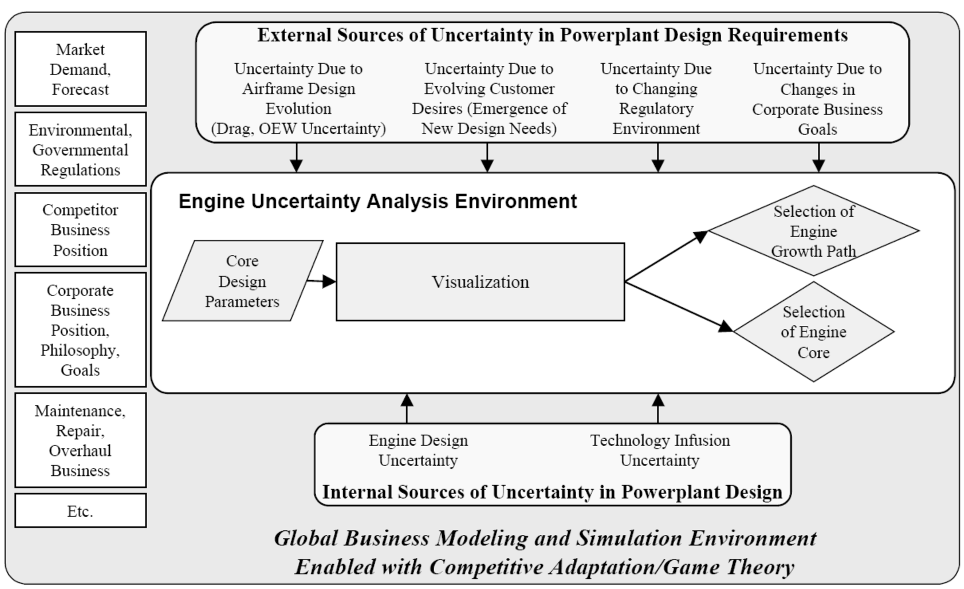

Figure 2.4: Research Vision Linking Design Uncertainty, Requirements Uncertainty, and Engine Design (Mavris and Roth, 2001).

One of the most challenging and interesting engine selection studies from both an engineering and managerial standpoint is the Boeing 777 program. After the U.S. Congress passed the Airline Deregulation Act in 1978 intense competition followed in both the airline and airplane markets (Kahn, 1988). In 1986 Airbus and McDonnell Douglas, two of the big three aircraft manufacturers, were nearing the end of the development of the A330/340 and the MD-11 respectively. Boeing was continuously profitable with the B747 but could not compete in the same market. Engineers initially wanted to develop a derivative for the B767 but could not agree with customers on the number of seats and range. They opted for a fresh start and a new design that promised to have the latest in navigation and flight control technologies, newer materials and more fuel-efficient engines. Furthermore, the B777 was planned to fill a new niche in the marketplace. Figure 2.5 shows how the B777 and its derivatives have managed to secure a broad range of seat capacity and range combinations in the market.

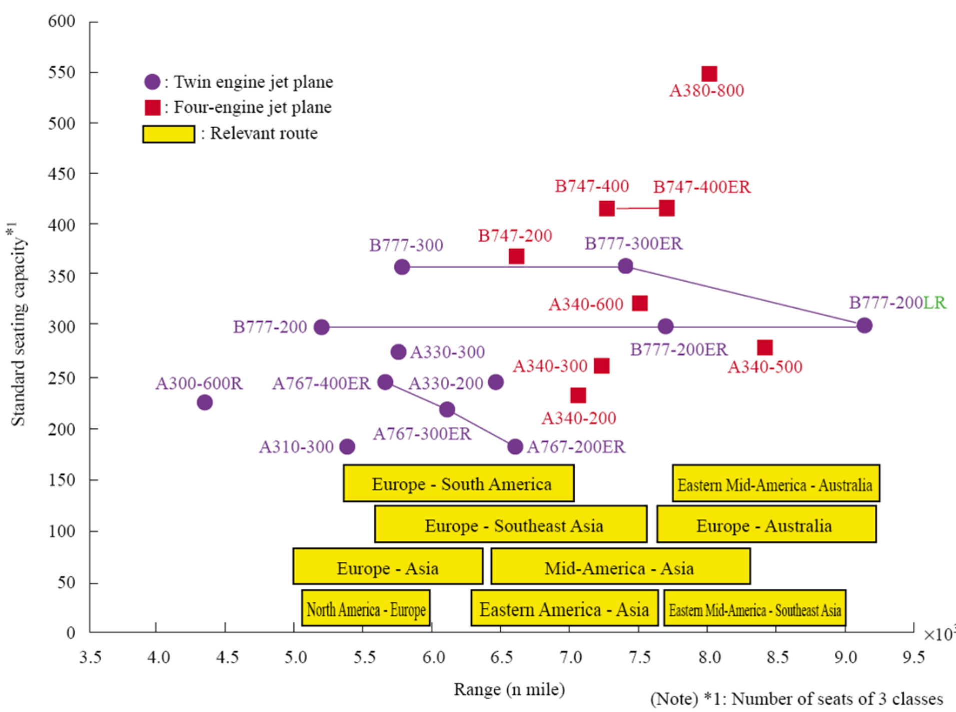

Figure 2.5: Seat and mile chart (2-aisle wide body aircraft) (Horibe et al., 2004).

United Airlines was the launch customer for the B777 and had a choice of three engine manufacturers: Rolls-Royce, General Electric and Pratt & Whitney. The available options were to either offer variants of existing engines or weigh the options in favor of designing and building a new engine type. General Electric decided to pursue a completely new engine and invested $1.5 billion into the development of a new fuel efficient design. Their strategy was to infuse new low emissions and noise technologies with Snecma's partnership and provide airlines with thrust growth options for commonality within the B777 family of future derivatives. United Airlines however, chose the engine Pratt & Whitney was offering purely on commercial grounds to power their airplanes (Sabbagh, 1996).

The choice of engine type is made for a whole host of reasons. Most experts, like Monteleone (2001) and Sabbagh (1996) agree that one of the most important metrics is the return on investment of the engine to the airline. Engine companies will compete for the best price and financial incentives as well as negotiate maintenance and support contracts. But fuel economy and efficiency are also important as they contribute directly to the operating costs of the aircraft. The potential for thrust growth is a significant advantage too. Moreover, the ability for engines to be standardized across the fleet by derating an engine for entry to service while providing growth capability for future thrust requirements is also attractive to customers (Ramsay, 2003).

It was up to the B777 engine manufacturers to take the best strategy in choosing the engine architecture as this would ultimately determine their economic success for the next 20 years to come. The GE90, General Electric's engine, was virtually all new technology. It had a wide chord composite fan blade, new combuster design and a very high pressure compressor that had not been implemented before. Although Pratt and Whitney's PW4084 was chosen to launch the B777-200 it did not have the same growth potential as the GE90. It's engine core had a proven track record with the Boeing 747-400 and later with the A330. One of its biggest advantages was its parts commonality with other PW4000 cores powering aircraft such as the B767 and MD-11. This commonality was popular among customers and was a deciding factor for those airlines whose savings in costs from service and parts resulted in offsetting the lower thrust growth potential and higher fuel consumption. As the B777 orders grew over the years and as airframe derivatives entered the market there was a need for more thrust and it was ultimately the GE90 whose core was best positioned to take advantage of more thrust growth. Figure 2.6 shows the fluctuating sales for all three engine providers of the B777 family for the past 10 years. For further sales data, the reader is referred to section D.2 of the appendix.

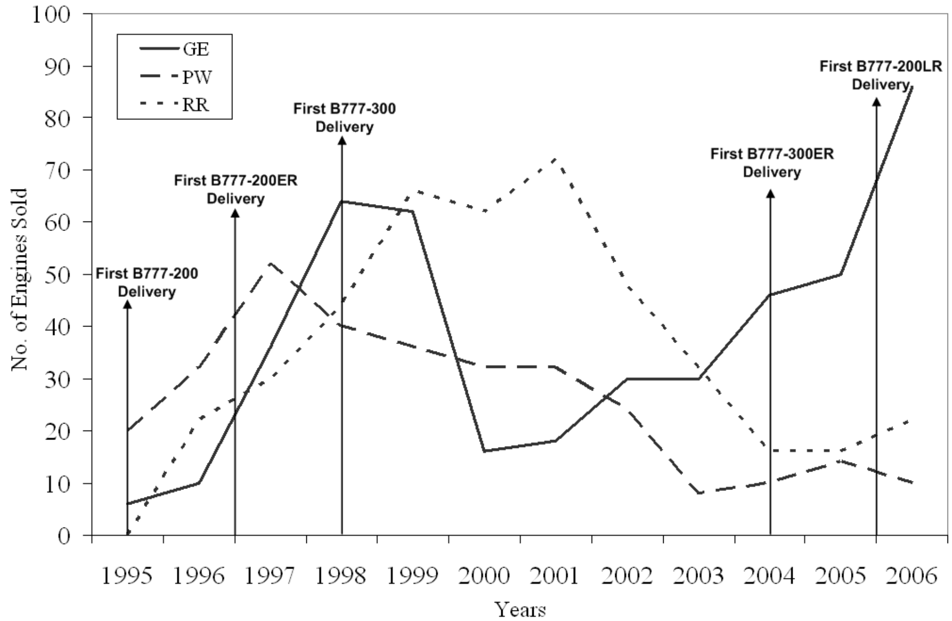

Figure 2.6: Boeing 777 Engine Sales (Based on deliveries made) (Boeing Commercial Airplanes, 2008).

Although Pratt and Whitney may have secured the launch of the B777-200, together with Rolls-Royce they were unable to provide an option for the last two variants of the B777 family. The core architecture selection of the GE90 was a unique strategy that helped them maximize their return on investment in the latter years of the B777 program.

2.2 Modern Systems Design Methods

The way in which engineers design systems today has evolved from the once limited methods that were primarily employing qualitative measures to a more quantitative-based approach that includes analysis of economic factors, safety, certification, etc. A major advancement in the design process has been the study of life-cycle cost. Foerstemann and Staudacher (2004), Fossnes and Forsberg (2006), and Halliwell (1998) have shown that by the end of the research, development, testing, and evaluation phase (RDTE) approximately 60-70% of the life-cycle cost has been committed. Since life-cycle cost is an important contributing factor to economic success, designers have put a great deal of effort in designing for cost.

One of the goals of modern design methods and tools is to generate a better understanding of costs factors as well as provide a foundation for integrating life-cycle processes such as manufacture and support into the early phases of design. Efforts in Concurrent Engineering (CE) by Kusiak (1992) and Integrated Product Development (IPD) together helped pave the way for the establishment of Integrated Product/Process Development (Schrage and Mavris, 1995).

2.2.1 Integrated Product and Process Development

Integrated Product and Process Development (IPPD) is a design discipline that emerged as an effective way to drive Total Quality Management (TQM) in each stage of a product's life cycle. The philosophy behind IPPD is rooted in bringing together experts from the different phases of both product and manufacturing process development with the goal of maximizing life-cycle cost. Process and product trades are made with respect to the conceptual, preliminary and detail design sequence. An example of the modified Georgia Tech IPPD framework is illustrated in Figure 2.7.

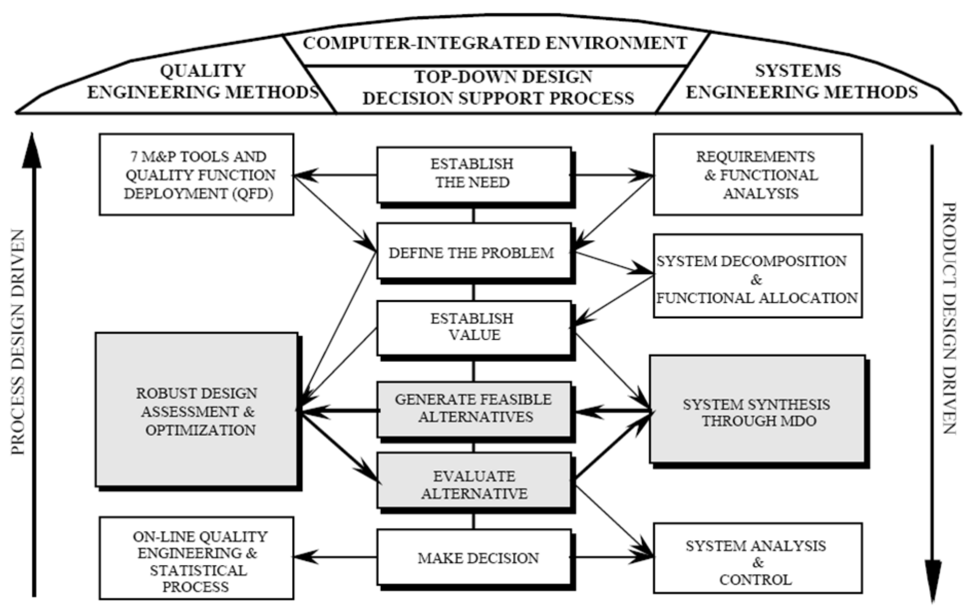

Figure 2.7: Georgia Tech Generic IPPD Methodology (Schrage and Mavris, 1995).

IPPD techniques have enabled entities managing complex programs to decrease programmatic risk as well as uncertainties associated with product redesign during the manufacturing and support stages (Department of Defense, 1996). According to Kirby (2001), by bringing knowledge and information forward in the design process through the use of IPPD techniques, decision-makers have greater flexibility in choosing affordable designs. There is also a greater likelihood that systems will perform better because of the cohesiveness of all integrated disciplines that play a part throughout a system's life cycle. For systems engineering design problems this process is typically non-trivial. The difficulty lies in determining what rational choice best meets the objectives or expectations. Hazelrigg (1996) lists:

> *"Two things that complicate almost all engineering decision-making processes: first, uncertainty on both outcomes and values and, second, knowing what to include in the universe of phenomena that needs to be considered in determining the outcomes of the options."*

2.2.2 Robust Design Simulation

Robust design is a technique that was originally developed by Taguchi (1987) to decrease product variability and improve quality in manufacturing processes. The goal was to eliminate as much of the variability during the design and manufacturing processes and thus stay as close to the design specification as possible. The technique is carried out by identifying the settings of design parameters that best minimize the effects of variation in manufacturing on the performance of the design (Dieter, 2000).

In the aerospace community the concepts of Robust Design were brought in to address the need to control interdisciplinary interaction as well as combine both design and manufacturing into a systematic framework such as IPPD. A Robust Design Simulation (RDS) methodology was created that embodied techniques like Design of Experiments (DoE), Response Surface Methodology (RSM), and Monte Carlo Simulation (MCS) in order to support the IPPD framework. One the goals of RDS is to identify sources of variability in order to reduce life-cycle costs. Bandte and Mavris (1995) developed a way of assessing economic uncertainty by employing RDS techniques within an IPPD framework for the development of a High Speed Civil Transport (HSCT) vehicle. Furthermore, the use of probabilistic measures of robustness in multidisciplinary design have been successfully shown to help manage uncertainty in complex aerospace design problems (DeLaurentis and Mavris, 2000).

2.2.3 Probabilistic Design

The term probabilistic design refers to the approach used in systems engineering to facilitate decision-making. Probabilistic tools help identify designs that are least sensitive to random variability in performance of systems. These variability effects are significant when optimizing for quality and reliability and are found to be most useful in fields like manufacturing and systems engineering. Probabilistic methods incorporate techniques such as robust design, parameter design and design for Six Sigma.

The use of probabilistic methods are found to be most beneficial whenever there is sufficient uncertainty to cause a significant variation in the response. This situation is most common when the design requirements are not well known or are likely going to change throughout the design process. The design of revolutionary vehicles is a prime example where designers would employ probabilistic methods in order to account for changes in mission requirements and uncertainties associated with the maturation of embedded technologies (Mavris, Roth and Elliott, 1998; Roth et al., 2004).

Aircraft engine design benefits from probabilistic methods because it helps to estimate the uncertainties in engine component weights and performance as well as predict the overall performance of the system. The application of robust and probabilistic methods are becoming more widespread due to increased demand for safety and reliability and better prediction of technology performance. Studies by Mavris, Macsotai and Roth (1998) have shown how probabilistic design methods are employed throughout engine preliminary design that show the impact of changing engine cycle parameters on the performance of a large commercial aircraft.

Quantifying the uncertainty of customer specifications in engine design is an underlying goal of the this research. Customer requirements are specified as deterministic values that translate into constraints on the engine design space. However, these requirements rarely stay the same throughout the entire design process. These engine specifications are ultimately a function of aerodynamics, structures and other aircraft characteristics that will change whenever the aircraft design changes.

Mission uncertainty faced by the customer results in aircraft performance changes, yielding further variation of engine specifications. The vendor observes this variation of engine requirements as a migration of the engine design point. An illustration of this migration scenario is shown in Figure 2.8. Once the Modeling and Simulation Environment has been created, it is possible to challenge the required solution and possible deviations from the original needs. For instance, the solution point contains assumptions about:

1. *Structures:* If for any reason the initial design empty weight of the vehicle cannot be met when performance and takeoff gross weight are fixed, the engine manufacturer might be asked to lower the engine weight and or fuel consumption to help in reducing the overall vehicle empty weight or block fuel weight. Since there is usually a competing engine manufacturer waiting for an opportunity to enter the game, the company that is willing/capable of providing such a reduction might be the one chosen to power the vehicle. This is illustrated in Figure 2.8 where the maximum allowed engine weight is decreased, shifting the engine design point to (1).

2. *Aerodynamics:* uncertainty associated with the vehicle aerodynamics may lead to a degradation of the aerodynamic drag coefficients and properties which may increase the needed thrust to maintain the target cruise speed. This situation results in a displacement of the design point to location (2) as shown above.

3. *Mission Evolution:* Initial user needs usually change over time. These changes include variations in payload and range that regularly occur with time as new versions of this vehicle will be introduced on the market. This migration, due to growth needs, is denoted as (3).

4. *Combinations:* As shown in the Figure 2.8, it is possible to observe that combinations of these three scenarios can possibly change the design point.

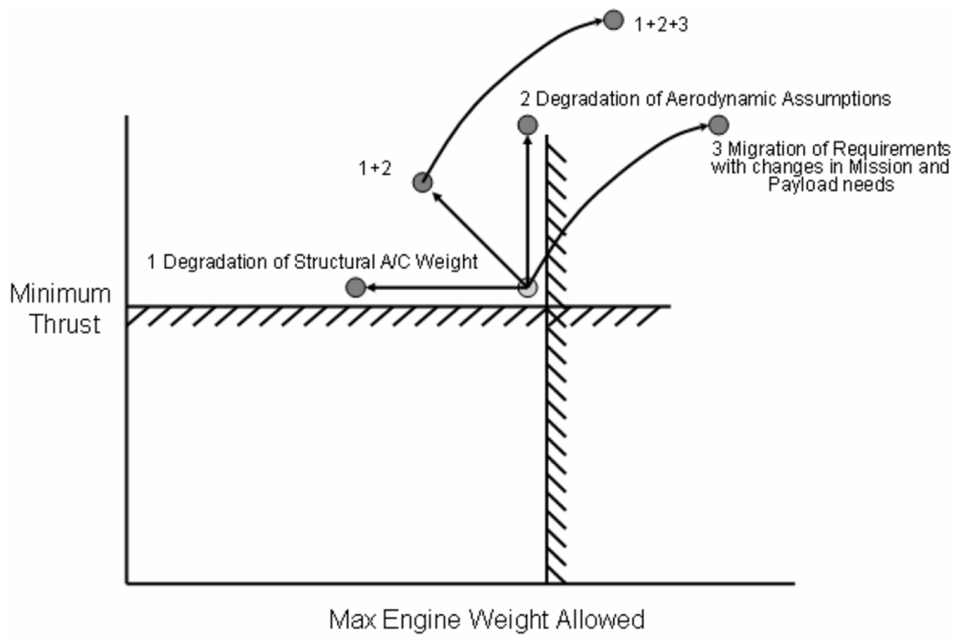

Figure 2.8: Migration of the Design Point with Uncertainty

Uncertainty in engine specifications is modeled by introducing variations in the assumptions made by the customer. For instance, the airframe manufacturer requires that the performance remain unchanged with a reduction in engine weight. As the aircraft design matures, the empty weight estimation at the outset is no longer valid. The customer needs to maintain range, payload, and performance. To balance this increase in weight, the airframe manufacturer may pass some of the weight reduction responsibility to the engine manufacturer, requiring a reduction in engine weight to meet the user performance needs. At this point, the engine manufacturer may no longer guarantee meeting the initial design requirements with full confidence.

Over recent years the field of probabilistic analysis has matured significantly with the emergence of new tools and techniques that have overcome the obstacles of using physics-based sizing codes that are deterministic in nature. The use of a surrogate model, which implies approximating a model with another model, is one of the best ways of building complex models that more accurately represent the physics-based codes. However, these complex models tend to have a large number of inputs and outputs meaning that a surrogate model usually will take a significant amount of time to construct. There is a tradeoff that is often made between the degree of complexity of the surrogate model to achieve accuracy and amount of time needed to construct that surrogate model. Oftentimes, designers will choose to create simplified models that sufficiently represent the more complex model and accept in return some measure of modeling error.

The biggest advantage of using surrogate models is to alleviate the burden of expending too much time running design codes that can usually take several minutes to run a single simulation. This is particularly common in aerospace design where using aerodynamics codes to perform design optimization and sensitivity analyses would need to be run thousands of times.

The first step in constructing a surrogate model is to identify which input variables are uncertain in the analysis. The creation of an accurate surrogate depends on the number of simulation runs which in turn is a function of the number of input variables used. However, as the number of variables increases more analysis runs will likely be needed which effectively increases the total simulation run time. Determining the most efficient number of runs or experiments needed to create a surrogate model with the minimum amount of effort is a broad field of its own. Experimental designs range from evaluating every possible input variable combination, commonly referred to as full factorial designs, to more efficient designs that leave out specific variable settings, known as composite designs. For a more detailed description and application of these designs, the reader is referred to more in depth literature by Montgomery (2001) and Barros et al. (2004).

After running the experimental designs through the analysis codes the data is regressed to build a linear regression model or a Response Surface Equation (RSE) (Myers and Montgomery, 2002). There are many popular methods besides Response Surface Methodology (RSM) such as Kriging, Gaussian Processes, and Neural Networks. Kriging models are advantageous for situations where a non-linear representation is needed (Simpson, 1998). Neural Networks (NN) are popular non-linear data modeling tools that are based on a mathematical representation of a biological interconnected group of neurons. They are most commonly found in the study of artificial intelligence and cognitive psychology. A surrogate model is constructed through a learning process in which Neural Networks must be trained during data-fitting. The statistical software JMP, developed by the SAS Institute Inc. (2007), combined with a surrogate modeling tool- Basic Regression Analysis for Integrated Neural Networks (BRAINN) (Johnson and Schutte, 2006) has greatly facilitated the creation of surrogate models and simplified the training process. (More information available in appendix B)

The process for implementing probabilistic analysis is illustrated in Figure 2.9. The representation of the modeling and simulation environment, via polynomials as expressed by the surrogate models, greatly facilitates the use of a Monte Carlo Simulation approach to obtain the probabilistic forecasts. Monte Carlo methods are simulation techniques that use random samplings to observe the statistical output of a mathematical system. They originated with famous physics researchers like Metropolis and Ulam (1949) and have been widely used in many operations research fields. A probability distribution of an appropriate

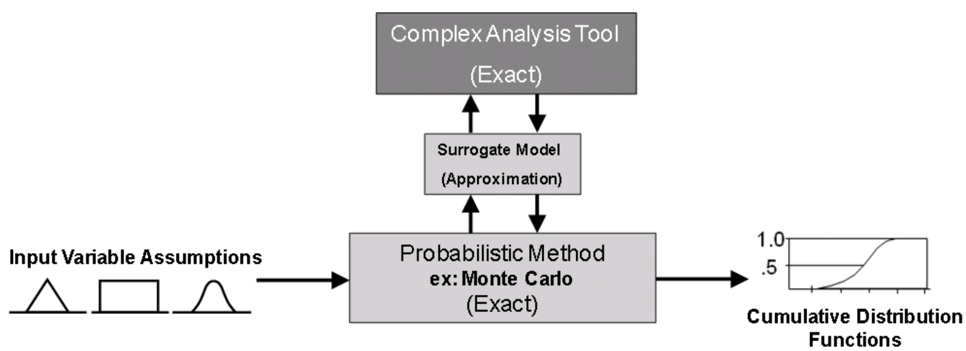

Figure 2.9: Probabilistic Design Method (Adapted from Bandte (2000))

shape is placed over the ranges set for each input variable. These distribution shapes can be normal, triangular, beta, or any other shape that best represents the perceived confidence and represent the probability of change of any given design metric (aerodynamic, structural, etc.). As the design development matures and the confidence associated with these estimates increases (i.e. reduction in the variability range) these shape functions will also be modified to reflect the change. Since the shape functions are time dependent this formulation may be characterized as a stochastic one.

The distributions defined are then provided as inputs into the computationally expedient surrogate model and a Monte Carlo simulation is performed. At the conclusion of this iterative process, probability distribution functions (PDF) or cumulative distribution functions (CDF) are generated for each of the responses of interest. Once these distributions have been evaluated for each metric of interest, and their corresponding correlation coefficients, ρ, have been determined (using the DoE obtained from observed results), joint probability curves may be introduced by superimposing two or more probability distribution functions (PDF) into the design space. Joint probability distributions (JPD) are useful in disciplines that involve the observation of more than one random variable (Li, 2007). Two probability distribution functions can be analyzed with a bivariate normal distribution in which each of the two random variables (x,y) are normally distributed. The resulting joint probability density function (JPDF) of the bivariate normal distribution is presented in equation 2.1 where "f" is the frequency of the JPDF, "x" and "y" are any parametric axes such as thrust and weight and "a" and "b" are specific values of x and y respectively. Equation 2.1 uses the normal distribution parameters, with mean μ, standard deviation σ, and correlation coefficients ρ of pairs of criteria and is illustrated in Figure 2.10.

$$f_{XY}(a,b)=\frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho_{XY}^2}}exp\left\{\frac{1}{2\rho_{XY}^2-2}\left[(a-\mu_X)^2-2\rho_{XY}\left(\frac{a-\mu_X}{\sigma_X}\right)\left(\frac{b-\mu_Y}{\sigma_Y}\right)+\left(\frac{b-\mu_X}{\sigma_X}\right)^2\right]\right\} \tag{2.1}$$

Joint probability decision-making is a popular method used to analyze various forms of uncertainty in multi-dimensional problems. The reader is referred to a more extensive overview of this field in the work by Bandte (2000) and applications of this method by other authors in this field (Li, 2007; Mavris and Briceno, 2003; DeLaurentis and Mavris, 2000).

2.3 Strategic Analysis and Planning

A principle goal in this dissertation is to investigate the spectrum of project selection strategies that best position manufacturers in a competitive market. To better understand the selection process and its purpose in the overall strategic vision of an engine company a review of the business structure of an organization is warranted.

Corporations have varying levels of strategy. Corporate strategy is developed by the top-level management to give a broad direction into corporate values, culture, goals and

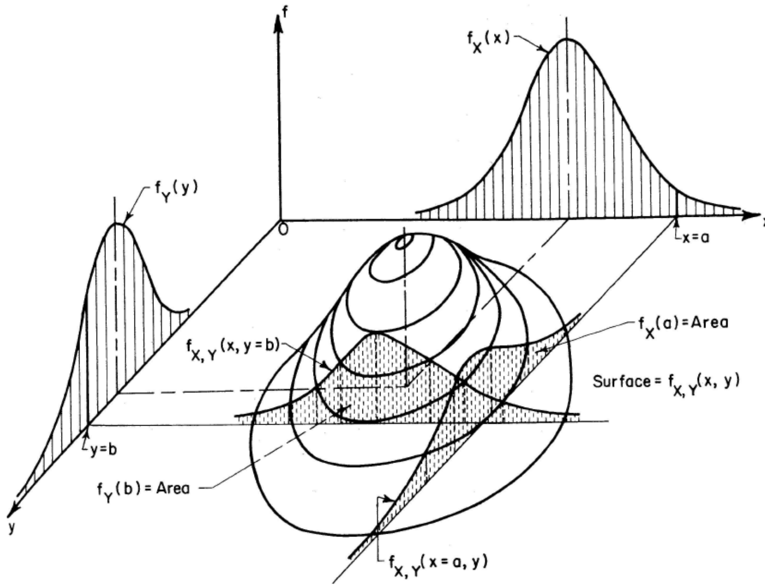

Figure 2.10: Joint Probability Distribution (Ang and Tang, 1984)

missions (Collis et al., 1999). Under this global corporate strategy there are often functional or business unit strategies. Functional strategies are limited to the domain of each departments' functional responsibility within the overall corporation. These include new product development strategies, human resource strategies, financial strategies, marketing strategies, legal strategies and information technology management strategies. Most companies however, have structured their organization into semi-autonomous strategic business units (SBU) that are responsible for their own budgeting, new product decisions, etc. The lowest level of strategy is operational strategy which deals with day-to-day operational activities such as scheduling criteria. This hierarchical strategy structure describes the types of strategies envisioned within a corporation. The aggregation of strategies in either an SBU or broad corporation is synthesized into the *business strategy* of the firm.

> *"At the heart of business-level strategy is the objective of developing a firm-specific business model that will allow a company to gain a competitive advantage over its rivals in a market or industry". (Hill and Jones, 2004)*

Strategic planning is a fundamental activity at all levels in an organization. It involves defining objectives or goals and developing strategies to reach those objectives. The term *strategic* implies that the objectives are typically addressing the *big picture*. It is distinguished from *tactical* planning which focuses on local or individual activities. Strategic plans are often viewed as road-maps that provide a structured process to guide the decision-making towards achieving a vision within an organization.

The strategic plan is formulated in the form of a business case which provides direction in areas like financial strategies, human resources, information technology deployments, marketing strategies, etc. It involves decisions regarding the firm's target market, product mix and technology selection as well as its ability to allocate resources and prioritize projects (Krishnan and Ulrich, 2001). At the product strategy and planning level decision-makers will want to know what market and product strategies maximize the probability of economic success. The objective of strategic plans is to match the organizations resources and core competencies with the external environment. It also allows companies to establish a sustainable competitive advantage in a market. A major aspect of strategic planning is to identify potential investment opportunities. The research and development phase of product development is a prime candidate for strategic planning due in part for the large amounts of capital spending. *"Unfortunately, traditional methods of investment in technology development programs or closing the business case are ad hoc and lack rigor"* (Kirby et al., 2006). Technology programs form a significant part of research and development spending. Knowing if and how the technology will be aligned with the future business strategies is the motivation for initiating a proper strategic assessment. There are a variety of qualitative and quantitative decision-making tools that provide a structured approach to developing strategy (Rouse, 1992).

2.3.1 Strategic Prioritization and Planning Process

One such tool is the Strategic Prioritization and Planning (SP2) process developed by Kirby et al. (2006). This process focuses on the resource allocation of technology programs in research and development phases. It builds on techniques in the quality engineering domains and employs characteristics of both Quality Function Deployment (QFD) (Akao, 1990; Dieter, 2000) and Six Sigma techniques. A method that integrates the customer requirements and engineering capabilities in a quantifiable manner is the Quality Function Deployment

. This is a problem-solving and planning tool that translates the customer needs and engineering characteristics into a strategic plan. It's a qualitative method that assists design teams with categorizing customer requirements and systematically matching each requirement with an engineering characteristic. In addition, it provides a benchmarking of the competition and allows for a competitive strategy formulation. The SP2 process was exercised in a recent study for Congress as part of a five year research and technology plan for U.S. aviation (National Institute of Aerospace, 2005).

Throughout the strategic planning of programs it is often challenging to map the customer requirements to technology options. One of the thrusts of the SP2 process is its ability to reduce the dimensionality by creating a traceable link between technology options and requirements and thus facilitating their decomposition. The SP2 process is divided into five steps, namely: Define the customer requirements, Define the system attributes, Gather technology information, Technology information review and validation, Strategic planning execution. A parallel approach for strategic planning of technology portfolios is called Strategy Optimization for the Allocation of Resources (SOAR) is described by Raczynski (2008).

2.3.2 Product Development Decisions

An important aspect of strategic planning is the selection of R&D projects within the organization. A project can be defined as a *"finite endeavor-having specific start and completion dates-undertaken to create a unique product or service which brings about beneficial change or added value"* (Project Management Institute, 2004). In aerospace design an R&D project entails the collaboration of organizational functions as identified in Figure 1.4 for the purpose of introducing a product into the marketplace. Of interest in this research are the decisions associated with the generation of new products within the overall strategic process.

There is no single universal approach to product design and development. However, within the business and engineering communities it is widely accepted that there are at least four main organizational perspectives that deal with product development. Krishnan and Ulrich (2001) compile these perspectives in table 2.1.

A continuing challenge to product development research is to identify means of bridging

Table 2.1: Comparison of Perspectives of the Academic Communities in Marketing, Organizations, Engineering Design, and Operations Management (Krishnan and Ulrich, 2001).

	Marketing	Organizations	Engineering Design	Operations Management
Perspective on Product	A product is a bundle of attributes	A product is an artifact resulting from an organizational process	A product is a complex assembly of interacting components	A product is a sequence of development and/or production process steps
Typical Performance Metrics	"Fit with market" Market Share Consumer utility (Sometimes profits)	"Project success"	"Form and function" Technical performance Innovativeness (Sometimes direct cost)	"Efficiency" Total cost Service level Lead time Capacity utilization
Dominant Representational Paradigm	Customer utility as a function of product attributes.	No dominant paradigm. Organizational network sometimes used.	Geometric models. Parametric models of technical performance.	Process flow diagram Parametric models of process performance.
Example Decision Variables	Product attribute levels, price	Product development team structure, incentives	Product size, shape, configuration, function, dimensions	Development process sequence and schedule Point of differentiation in production process
Critical Success Factors	Product positioning and pricing Collecting and meeting customer needs	Organizational alignment Team characteristics	Creative concept and configuration Performance optimization	Supplier and material selection Design of production sequence Project Management

these perspectives to help promote cross-functional ideas and communication. Efforts have been made by Ettlie (1997); Balachandra and Friar (1997) to integrate the design of new products by having the various disciplines and organizational functions that span the life-cycle of new products and services collaborate together. In particular, Ettlie (1997) shows that integrated approaches to design assist in providing more knowledge and reduced uncertainty about market needs throughout the development process. Incidentally, the study also mentions that although integrating marketing, R&D and production teams will promote new product development success, there is still a need for strategic direction and knowledge of customers and competitors to further that success.

One the main roles of marketing teams in engineering firms is to help identify customer needs, product opportunities and market segments and is referred to loosely as the market research phase of design. Marketing is *"about understanding how people make buying decisions and using this information in the design, building, and selling of products"* (Dieter, 2000). They are responsible for helping the firm successfully sell a product or service in a specified market. The marketing department is the interface between a firm and its customers. Their goal is to acquire new customers and expand relationships with existing customers. A driving goal in this research is to understand how to utilize information from marketing teams in the form of customer needs and market competition to help further the selection process of concepts in design. Mansfield and Wagner (1975) suggest market analysis should be performed earlier in the R&D stages of product development.

A key challenge is evident in the cross-functional flow of information between marketing, operations, and engineering design teams. Each organizational function will have specific responsibilities regarding the development of a new product. Figure 2.11 illustrates the how the web of interconnected decisions between such functional teams. Authors like Balachandra and Friar (1997); Krishnan and Ulrich (2001) argue that each functional team will make product development decisions based on information within their area of expertise and will often ignore considerations arising from the functional interdependencies between teams.

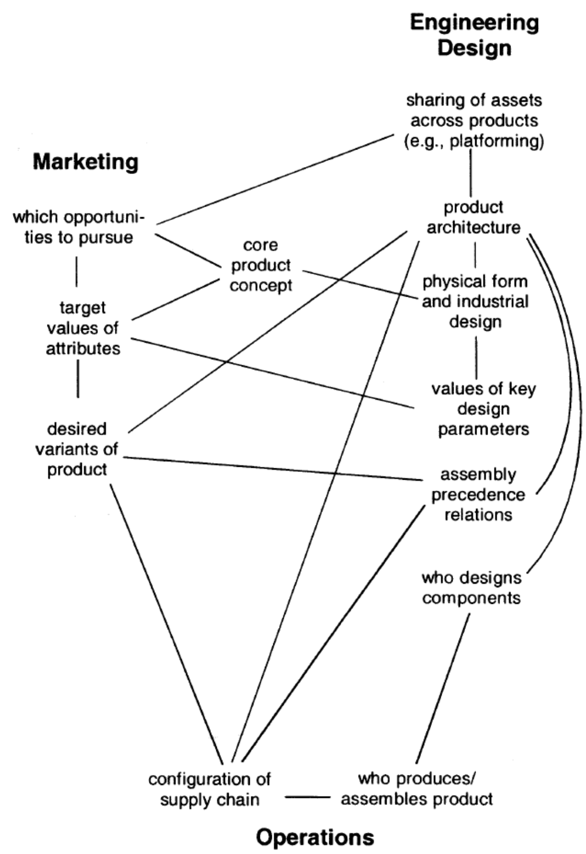

Figure 2.11: Clustering of Product Development Decisions by Traditional Functional Categories (Krishnan and Ulrich, 2001).

Most project initiations are born from some type of marketing analysis which investigates the various opportunities to pursue. However in many cases projects often get a boost from technology programs already in progress within the organization.

2.3.3 Market Segmentation

Most business strategies include some type of marketing strategy. There are many types of marketing strategies that deal with market dominance, product differentiation, market segmentation, innovation, growth, etc. Marketing strategies are derived from the marketing plan which is created based on the overall business strategy. In many competitive situations, the quality of a market strategy often determines who wins. Although marketing strategies are not formulated in engineering conceptual design, processes like market segmentation, described by Seepersad et al. (2002), are widely used to divide a global market into subset groups with homogeneous characteristics and thus facilitate the design selection process. Firms will segment markets based on important differences in customer needs or preferences in order to gain a competitive advantage (Hill and Jones, 2004).

Market segmentation is also employed as a robust design concept according to Rothwell and Gardiner (1988). They define it as a design *"that has sufficient inherent design flexibility or 'technological slack' to enable it to evolve into a significant "design family" of variants. Essentially, a robust design is one that can satisfy the evolving needs of a "set" of user segments."* This is an important technique that is employed in the marketing department but not necessarily considered by conceptual designers.

Marketing teams have a large variety of business tools that they employ to formulate the appropriate strategy to target the customer. These tools however are rarely, if ever, employed at the engineering conceptual level. Instead, many engineering departments will have their own simplified version of a customer value tool or marketing tool to assess how well the product will perform in the market. For this reason, these designers are reluctant to carry out competitive market analyses on their technical designs because of the lack of trustworthy information they have and data they produce. Preliminary designers therefore have difficulty in identifying the impact of the competitive element from the market on their technical design choices.

2.3.4 S.W.O.T. Analysis

A common strategic planning approach best suited to help develop a competitive business model is to identify a firm's internal Strengths and Weaknesses and its external Opportunities and Threats (SWOT) (Humphrey, 1970). A firm's internal strengths are those unique skills or distinctive competencies that help build and sustain a competitive advantage. Likewise, there exists weaknesses within a firm that restrict it from achieving its objectives and that may need improvement. A SWOT analysis will scan the external environment and identify where the best opportunities exist based on specific firm objectives and resources. The firm's external operating environment will also likely contain threats that may prevent the firm from achieving its superior performance.

One of the advantages of using SWOT at the beginning of any strategic planning initiative is that it provides a quick assessment of the external environment. Decision-makers can determine how significant the threats are from technological or marketplace changes, competitive positioning or other macroeconomic factors. For industries such as aerospace where globalization is prevalent, analyzing the market environment will facilitate the decisions that need to be made to determine if there is sufficient competitive advantage in the global marketplace.

This analysis tool is useful for auditing the overall strategic position of a business and its environment. If the the group of individuals involved in the analysis share homogeneous characteristics this strategic planning tool can be rewarding. However, the technique may not lend itself to large heterogeneous groups as it may be difficult to agree upon specific strengths or threats and can limit the potential for compromise. It is a powerful brainstorming tool with qualitative capabilities of assessing strategic factors but has no formal methodology that can provide quantitative benchmarks that may help reduce any disagreements or confusion.

2.4 *Project Selection Studies*

There are various studies that have been performed in the area product development that focus specifically on competitor behavior. Figure 2.12 illustrates a taxonomy of the review of game options in selecting research and development projects. A review was conducted to determine which studies would be most beneficial in developing a decision-making framework. Since this research investigates the selection of an engine project based on a variety of different engine options, the study of a portfolio of projects makes most sense. Also, the analysis of a one-stage game under competitive conditions is assumed as well. More on those assumptions are available in Chapter 4.

A major contributor to this research was the study performed by Ali et al. (1993) which presents an approach to selecting pioneering or incremental innovation strategies for product development projects. Studies by Dasgupta and Maskin (1987); Bhattacharya and Mookherjee (1986); Henriksen and Traynor (1999) have also demonstrated various techniques in portfolio selection . Others have analyzed R&D portfolios within an engineering environment with the aid of decision and risk analysis. Findings show that most of the models in the management literature does not incorporate the effect of competition on resource allocation.

2.5 Competitor Analysis

Firms make investment decisions for various strategic reasons. The difference in making strategic investment decisions from other types of decisions is that firms must make them by taking into account the reaction of other firms and its potential effect on its own value. When an airframe manufacturer (customer) initiates the design process for a new product, engine manufacturers must quickly decide how to respond to the emerging needs of the vehicle. The time available to act varies according to the stage of the design process. The engine company (vendor) must decide if the project is worthwhile to pursue and generally employs some type of economic analysis based on return of investment, net present value or cost-benefit ratio. New aircraft also have a higher potential for fierce competition since no company may have a distinct advantage in producing the specialized engine needed. Decision makers deal with these issues by evaluating these assessment metrics based on personal insights or expert opinion usually in the absence of any in depth analytical assessment. Decisions are usually based on the ability to meet a set of requirements that is provided to them by the customer, while ensuring a reasonable return on investment. At this point the vendor will have to decide whether to accept or push back on some of these requirements. In many cases, the

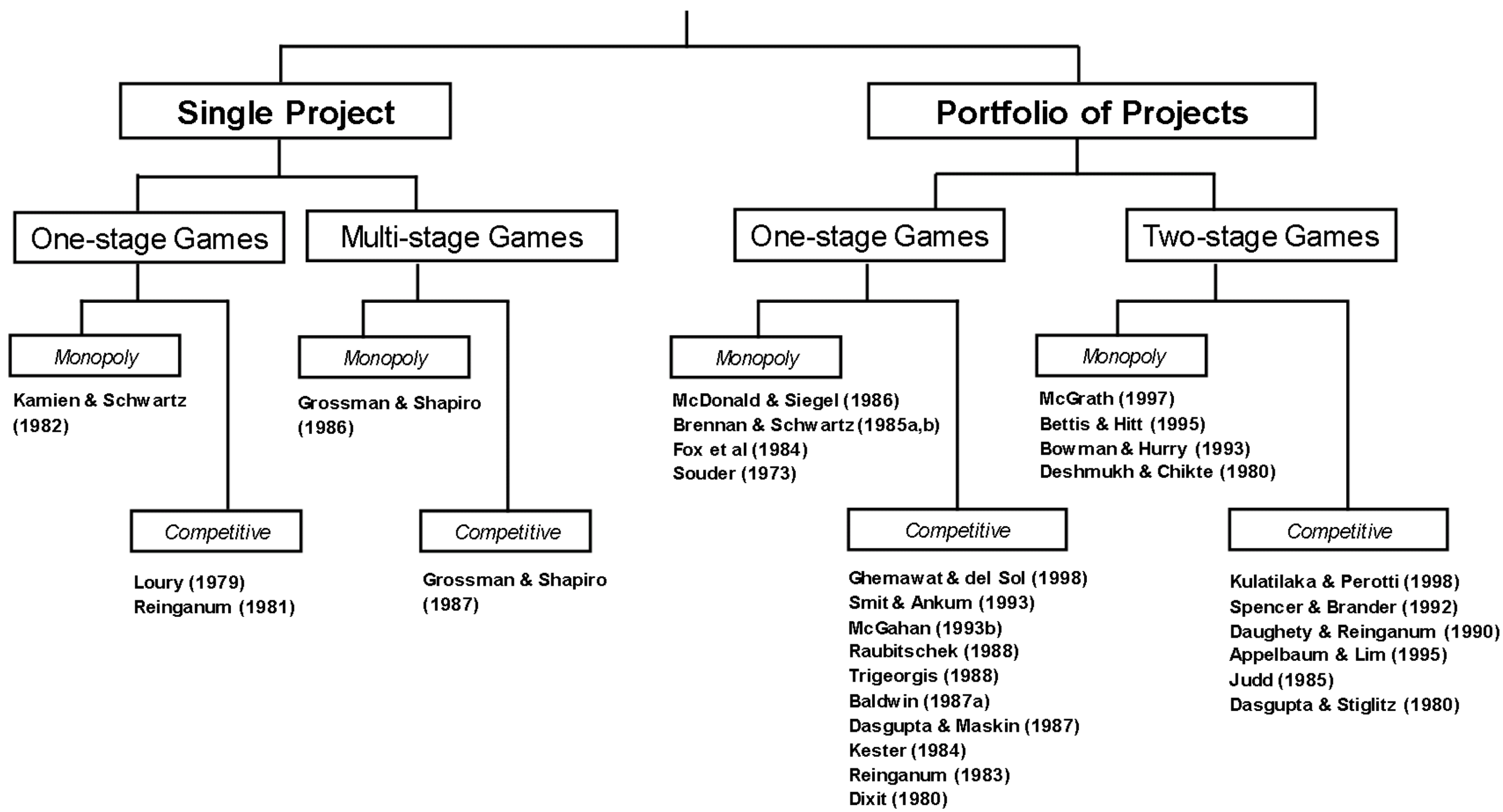

Figure 2.12: Taxonomy of Game Options in Selecting R&D Projects (Updated from Ali et al. (1993))

vendor feels pressured to secure the contract due to competition and to offer assurances and guarantees on the over-specified requirements that sometimes cannot be met simultaneously. However, uncertainty exists in the design of the vehicle and engine as both progress through the development. As a result, increased development costs or terminations of the contract occur if initial guarantees are not met.

Engine manufacturers will typically compete for market share by means of complex negotiation. There are few established methods that can model this aspect of competition. Most of the negotiation with customers deals with formulating financial incentive agreements which are contracts that specify the details of the purchase and maintenance of the engine. Engine companies will typically sell engines at an attractive price so long as the customer commits to a long-term maintenance contract with them. A significant portion of engine profit comes from post-production parts support and maintenance. Marketing credits and concessions are common in the industry to attract customers and gain market share. Throughout these negotiations the engine marketing department will focus on selling the engine via financial incentives but not necessarily focus on the engine/aircraft advantages over the competition.

The marketing teams will meet with the customer and layout a personalized study of how their engine will meet the needs of the customer. An in depth risk analysis regarding the economic performance of the engine is common. The marketing team will also usually demonstrate how their engines can satisfy the operating cost requirements through a route network analysis. These methods are beneficial for marketing teams to identify their advantages over the competition but what is important to remember here is that the majority of this customer analysis occurs once the engine has been partially designed. Conceptual engineers ought to take advantage of some of these methods early on in the design process to better understand where they could potentially stand in a competitive market. Anticipation of a competitor's response is an essential part of developing a competitive strategy.

2.5.1 First-Mover Advantage

The development of an entry strategy for a market is a key management decision that can have a significant impact on the success of a project. The elements of this strategy will determine the positioning of the product in the marketplace as well as its long-term success or failure. There are many questionst that need to be addressed in order to forulate the best strategy: should the firm be a pioneer, a fast follower or a later entrant? how should the firm enter the market- internal development, acquisition or joint venture and with how much R&D investment? Is there a sustainable competitive advantage to adopt?

In many industries firms tend to push a product into the market before it is ready and still with many defects left to be addressed. This is most common in the computer software industry. However, in aerospace design, engine manufacturers will often make performance guarantees, like fuel consumption, to the airframe manufacturer in order to be selected to launch that airframe. The reason for this haste into the market is because firms that introduce their product first will usually have access to a larger potential customer base because none of the customers will have purchased the product as yet.

There exists a distinctive market advantage to firms that are able to enter first. Although this is the most common situation, if there are too many defects this strategy may backfire. Several studies have shown that formulating a game with the ability to address this first-mover advantage is beneficial to understanding the significance of this type of strategy on return on investment (Schmalensee, 1982; Robinson and Fornell, 1985; Fershtman et al., 1990; Ettlie, 1997). The lead time between a firm's entry and a response by the follower benefits the first-mover in two ways according to Kerin et al. (1992):

1. During the time when there is no competition, the [firstmover] is, by definition, a monopolist, and may use this position to gain higher profits than would be possible in a competitive marketplace and/or increase the size of the total market.

2. After the entry of the competitors, the [first-mover] has established market position and leaming curve economies, which may allow it to retain a dominant market share and higher margins than imitators.

Three primary sources of first-mover advantages are described by (Lieberman and Montgomery, 1987): 1) technological leadership, 2) preemption of assests, and 3) buyer switching costs. Of interest to this research are the advantages associated with technological leadership. The second and third sources are less applicable to aerospace systems. There are key advantages in the form of a learning curve where production costs decrease with an increase in output for early entrants. They also suggest that technological advantages in the form of patent and R&D races are proportional to the R&D investments made by those firms. They also discuss first-mover disadvantages, which are advantages to late entrants such as: 1) the "free-rider" effect, taking advantage of R&D, buyer education, infrastructure, 2) resolution of technological and market uncertainty, 3) technological discontinuities that provide "gateways" for new entry, and 4) incumbent adaptability issues with the environment; difficulties for the incumbent to respond to competitive threats.

Development of market-entry strategies is an activity that typically takes place by marketing managers. However, these decisions are dependent on the technological progress and capabilities of the firm. The effects of market entry-timing are important to engineers because it allows them to evaluate their project options against the competition for different entry scenarios and therefore assist in the project down-selection. The proposed game structure in this research presented in Chapters 4 and 5 introduce these first-mover advantage parameters to study various market scenarios.

2.5.2 Modeling Competition in Systems Engineering

The concept of competitive analysis was introduced in the previous chapter as an essential activity to support strategy formulation in systems design. The analysis of competition is not a straightforward procedure common to all competing entities. The process itself depends on the type of competition occurring and on the type of parties competing. For instance, the competitive analysis of a firm seeking to increase its share in a particular market will differ from the analysis of a country seeking to beat an enemy in a war. Furthermore, the analysis process may transcend many levels of strategy formulation. The firm seeking to gain market share may be targeting a local market where strategy formulation is controlled by a small branch of the firm or even a specific department within that branch. Conversely, the firm may perform a competitive analysis on a more global scale that targets a broader market(s) and has a larger strategic impact on the firm. Similarly, a country in a war situation will have local battle strategy formulations and a more global approach to winning the war. The procedure of competitive analysis thus highly depends on many factors.

The review of existing competitive approaches is driven primarily by the factors or assumptions associated with this research. A fundamental premise in this research is that the proposed methodology is employed by conceptual design engineers that have control over local design parameters. Therefore the competitive analysis is being performed at the engineering conceptual level by manipulating system design parameters. Another significant assumption is that metrics like customer satisfaction, net present value, market share, etc. are introduced into the competitive analysis so that the competition and the analysis thereof can be more accurately represented. It was affirmed previously that competitive analysis performed in conceptual design lacked rigor and fidelity. These factors play an additional role in the search for appropriate techniques to develop a competitive analytical framework.

The objective again is to enable *technical* design teams to carry out a competitive analysis at the conceptual design stage and to observe how that may impact their design decisions. The immediate solution would be to borrow the powerful tools used by the marketing department and integrate them into the technical design decision-making process. In the aircraft engine industry for example, there exists collaboration between the marketing department and preliminary design engineering. However, this usually means that engine information or market data is transferred but there is not very much joint analysis taking place. This is often because many of the business tools are not well understood by engineers. Another approach is to use the existing version of the customer value tool used by engineers in conjunction with more advanced decision-making techniques that do not have the strategy development benefits of business tools but that still allow for some more rigorous competitive analysis.

The Boeing-Airbus competition described earlier is an example of a game in the aerospace industry. Competitive situations have driven decision-making in many different industries. The satellite-based mobile phone industry launched by the Iridium project in the late eighties is an example of how the engineering team lost track of changing consumer patterns and competing products which altered the original business plan and had a significant effect in their market share. A reminder here is that the business case must be revisited and continuously updated at every point in the design process. Hazelrigg (1996) describes other examples of games frequently encountered in engineering practice are the following :

- Engineering system design in a competitive marketplace
- Contract and subcontract negotiation
- Setting a research and development policy in support of a product that is produced in a competitive marketplace
- Proposal writing and bidding
- Purchasing engineering goods and services
- Setting standards for a class of products or a service
- Establishing cooperative agreements for the design and manufacture of an engineering system

Although there are numerous competitive situations in commercial design problems, means to analyze them are not as widespread. Porter (1998) claims that a central aspect of strategy formulation is perceptive competitor analysis.

> *"The objective of competitor analysis is to develop a profile of the nature and success of the likely strategy changes each competitor might make, each competitor's probable response to the range of feasible strategic moves other firms could initiate, and each competitors' probable reaction to the array of industry changes and broader environmental shifts that might occur."*

One approach in competitive analysis is to use mathematical-based modeling of strategic behavior (Aubin, 1979; Fudenberg and Tirole, 1991). These models remove some of the subjectivity from the decision-making that occurs when analyzing competition. This type of modeling however is found primarily in the economic, business and military applications.

One of the most challenging aspects of competitive analysis is data collection. In order to answer many of the questions posed earlier, there is a need for gathering intelligence data on competitors and information about the competitive game. There are several sources and means to obtain this information but it can often be expensive and time-consuming. Furthermore, the compilation of such data for a sophisticated competitor analysis can also be overwhelming if there are many assumptions and uncertainties about this data. A competitor intelligence system proposed by Porter (1998) is outlined as a mechanism to organize such data to insure that the process is efficient. The reader is referred to Appendix D.1 for further information.

The evaluation of competition and the forecasting of future markets is inherently difficult because of the lack of information needed to accurately assess them. Companies rely on a variety of intelligence and forecasting techniques that may often display conflicting results. The decisions to incorporate this information that is gathered into the conceptual design is risky and difficult to justify. The models must also address the large number of assumptions that have to be made and the associated multi-level uncertainty.

Model fidelity in these analyses presents a design challenge to decision-makers as it can reduce the clarity between solutions. Reliance on empirical data in systems modeling usually constricts the new designs to historical models. Technical component models are instead derived from design fundamentals that includes physics-based logic. This has been successful in predicting overall performance systems metrics within a very small margin. The model fidelity in other less technical disciplines that analyze competition and market characteristics however, is limited to basic modeling capabilities with significant modeling uncertainty. Furthermore, existing modules function independently and when integrated together, computational speed is decreased. The competitive analysis is currently carried out by modeling similar engines with different technologies and evaluating them both in a representative model of today's market. Current modeling and simulation processes in systems design lack analytical capabilities to measure and quantify the uncertainty associated with competitor's strategy and market evolution. There is are no formal and systematic ways of dealing with competition in these stages of the design process. This research will seek to refine current competitor logic so that its impact can be more transparent when determining overall business return.

2.6 Summary and Benchmarking

The final section in this chapter is presents some of the top-level challenges that are foreseable in this research as well as hurdles that must be overcome prior to developing a methodology. A matrix of different techniques, methods, and tools is also presented to provide a sense of the many ways in which to tackle the research problem. Specific benchmarking criteria are also established to guide the formulation of the methodology.

2.6.1 Technical Challenges

Although competitive analysis is extensively performed by marketing teams the opposite is true in engineering design. The limited capabilities that exist for market analysis in conceptual analysis contain several drawbacks.The negotiations involving the customers and top-level engineering managers is frequently characterized by subjective decision-making. Oftentimes, political circumstance or motivation will drive these negotiations. This is also the case with discussions between engine and airframe manufacturers. At the marketing level, engine companies with significant market leverage will also use that as an advantage to guide the negotiations with the customer. This is a difficult aspect of the competitive problem to model due to the nature of the subject decision-making.

It is very challenging for design engineers to understand how their design choices will impact the engine's success in a market. Studies in the product development fields have shown that the use of game theory has been beneficial to understanding these impacts. However, in conceptual design of engineering these techniques are not well understood. It is very difficult to answer many of the business problems analytically. However, the use of physics-based models in conjunction with these project development studies provides a promising route to formulating a project selection framework within the realms of engineering design.

Both marketing and engineering departments rely heavily on empirical data to represent the economic and technical performance of the engine. Engineers will use past market scenarios where they have data that shows how they performed in the market and extrapolate

Table 2.2: Matrix of Alternatives of Methods and Processes for Literature Study

Planning and Project Down-Selection	Qualitative Business Planning	(for step) 1	Affinity Diagram	QFD	SP2 Process	Pugh Method	Other
	Economic models	1, 3 & 4	DCF	Cost-Benefit Analysis	Modern Portfolio Theory	Option Pricing	Other
	Interactive methods		Delphi process	Scoring	Unified Tradeoff Environment	Other	
	Descriptive Mapping	1	Morphological Matrix	Other			
	Multi-Attribute Decision Making	2, 3 & 4	MAUT	TOPSIS	AHP	OEC	Utility Theory
Uncertainty Analysis	Techniques	4	Monte Carlo Simulation	Analysis of Variance	Probability Theory	Fuzzy Set Theory	Sensitivity Analysis
	Processes	3 & 4	Robust Design	Surrogate Models	Joint-probability Decision Making		
Analysis of Competition	Qualitative Methods	1	SWOT	Five-Forces Model	QFD	PEST Analysis	
	Quantitative Techniques	5	Maximin	Dominance	System Dynamics	Agent-Based Models	AI
	Equilibrium Types	5	Pure Nash	Mixed Nash	Pareto-Nash	Other	
	Equilibrium-Finding Methods	5	Integer Programming	LP	Goal Programming	IEDS	Other

this data to simulate future scenarios. This limits them to forecast scenarios appropriately with little or no bias.

The final observation made in reviewing the literature in industry is that there exists a significant communication gap between those creating the business case with the engineering teams that must ultimately develop the product. The engine preliminary design process does not employ the in depth marketing analyses and therefore are unable to have a good understanding of how technical design parameters impact the success of the engine in a market. Simply modeling and analyzing the combined sources of requirements uncertainty is a major challenge. To include the additional complexity of considering this uncertainty in the context of the larger strategic business environment is even more difficult, and until recently, was so complex as to be nearly intractable. Fortunately, there are a variety of new ideas and techniques emerging in the fields of complexity science, game theory, and probability theory that offer promising new approaches to solving these problems.

2.6.2 Benchmarking

A broad review of literature was performed under three primary areas: planning and project down-selection, uncertainty analysis, and analysis of competition. Within each area various methods, tools and processes were investigated, some of which were described in depth in this chapter. Table 2.2 lists selected techniques and processes. Those highlighted in orange were investigated in depth and provide most of the foundation for the support of the proposed methodology. Those in green were investigated and are secondary approaches to solving a specific problem.

The selected methods are benchmarked against a set of criteria. A consumer reports type of study is created to facilitate the further selection of techniques to formulate the proposed method. It is also beneficial to qualitatively identify the strengths and weaknesses of methods to better understand where they can be utilized. Based on the characteristics of the problem defined previously, a series of criteria are elicited to qualitatively compare the possible techniques based on their different attributes:

1. *Problem Structure* - Ability to structure and enumerate problem strategies
2. *Parametric Capability* - Provides a means to explore areas of the design space and behaviors previously obscured by the complexity of the problem
3. *Uncertainty Modeling* - Facilitates the modeling of uncontrollable variables and includes forecasting capabilities
4. *Supports Rational Decision-making* - Provides a rigorous mathematical platform
5. *Quantifiable Competitive Behavior* - Analysis of competitive behaviors and trends
6. *Facilitates Visualization* - Promotes the visual identification of strategies to decision-makers
7. *Ease of Implementation* - The method can be used on a simple engineering problem

These criteria are meant to provide guidance in the method search and benchmarking phase. Specific techniques and methods were chosen from the Matrix of Alternatives and benchmarked against each other to determine which ones would emerge as most beneficial for this type of implementation problem. One of the challenges however, is to compare techniques that are not necessarily comparable within the same domain. For example, the SWOT and Five Forces model are methods widely used in business applications that have unique ways of formulating competitive strategies. However, although they focus on competitive analysis, they cannot be compared directly to techniques like game theory because of the vast differences in the contexts in which they would be applied. Table 2.3 benchmarks four strategic planning methods against the criteria established previously. The emerging techniques that

Table 2.3: Benchmarking of Strategic Planning Methods

	Strategy Planning Methods			
	SWOT	Five Forces Model	QFD	SP2 Process
Problem Structure	◓	◓	○	◓
Parametric Design Capability	●	●	○	◓
Uncertainty Modeling	◒	◒	◒	○
Rational (objective) foundation	◓	◓	◒	◒
Quantifiable Behavior	●	●	◓	◒
Visualization Capability	◓	◓	◉	◉
Ease of Implementation	◉	◉	◉	◉

◉	◓	○	◒	●
Excellent	Very Good	Good	Fair	Poor

will be of value to the development of the methodology are the QFD and SP2 process. The QFD is targeted more than the SP2 based on the ease of implementation. The focus is not on the resources allocation of technologies but instead on mapping the customer requirements with engineering characteristics to identify which engineering physical metrics emerge as being must important to carry through the analysis process. Therefore, it is determined that the QFD approach will be most beneficial to this type of problem.

Based on the techniques and methods investigated in this literature review it was determined that they all had enabling capabilities with respect to this research. The benchmarking in Table 2.4 indicates that game theory is a beneficial technique based on the criteria specified and will be reviewed in depth in Chapter 3. Agent-based models and system dynamics can handle competition but game theory is faster and more light weight in terms of its implementation into practical application involving only two competing agents. The strengths of agent-based and system dynamics models is that they can analyze non-equilibrium and nonlinear problems better but they require several simulations to converge on solution. Game theory has a mathematical foundation which provides a quick way of computing simple equilibria. The purpose of this chapter was to highlight potentially useful

Table 2.4: Benchmarking of Competitive Analysis Techniques

	Competitive Analysis Techniques		
	Game Theory	Agent-Based	System Dynamics
Problem Structure	Good	Good	Good
Parametric Design Capability	Very Good	Very Good	Very Good
Uncertainty Modeling	Very Good	Very Good	Very Good
Rational (objective) foundation	Excellent	Fair	Fair
Quantifiable Behavior	Excellent	Excellent	Excellent
Visualization Capability	Very Good	Very Good	Very Good
Ease of Implementation	Very Good	Fair	Fair

Excellent Very Good Good Fair Poor

techniques that will enable the creation of a competitive analysis process for conceptual design.

Chapter III

GAME THEORETIC TECHNIQUES

3.1 Introduction to Game Theory

In 1944 mathematician John von Neumann and economist Oskar Morgenstern published their research in book entitled Theory of Games and Economic Behavior (von Neumann and Morgenstern, 1944). This provided the foundations for the formal analysis of competitive interactions in economics and business strategy though its scope diversified to fields in political science, sociology, and evolutionary biology. In its very basic form, game theory is a tool for understanding how decisions affect affect each player. Until the establishment of formal game theories, economists believed that firms could ignore the effects of their behavior on the actions of other firms. This assumption would work in a monopolistic environment or when competition was perfect but in the majority of cases was misleading.

Game theory presents a logical and mathematically based means of approaching problems involving competitors and decision making. A game is a model of a competitive situation, and game theory is a set of mathematical methods for analyzing these models and selecting optimal strategies. Even without complete knowledge of an opponent's decisions or resources, game theory is useful for enumerating the decisions available, and evaluating these options, or "moves" in a game sense. When a competitor's investment decisions are contingent upon the other's moves, a wait-and-see approach may not always be advisable and therefore a more rigorous game theoretic approach is necessary. It is a helpful tool in valuating strategic decisions because it includes a means of understanding or predicting the way in which competitors will behave and further provides an equilibrium strategy with values for those decisions.

Game theory thus could be the link between engineering decision making and business strategy by describing engineering decisions as the allocation of resources, and business decisions as the assessment of return in a game model. The game model itself can contain sophisticated company analysis codes and simplified descriptions of competitors. "*Game theory provides a method for understanding and perhaps guiding the optimization process. As such it provides an important management tool for use in decentralized design*" (Vincent, 1983). Game theory may involve the application of simple optimizations of combinatorial problems, potentially including the application of genetic algorithms that compete to determine which emerges with the best solution.

To successfully create the decision-making framework proposed in this research, a general methodology for engine selection needs to be formulated that will require the application of advanced methods to find the best set of strategies possible.

> "Game theory's most valuable contribution has been to show that rationality is effectively undefinable when competitive actors have unlimited computational capabilities for outguessing each other, but that the problem does not arise as acutely in a world, like the real world, of bounded rationality" (Simon, 1996).

There are two types of games that are most commonly used to model interactive behavior. Hazelrigg (1996) describes them below.

> "A cooperative game is any game in which players can make binding commitments."
>
> "A noncooperative game is any game that is not a cooperative game, this is, a game in which the players are not permitted to make binding commitments."

Noncooperative games are good representations of the competitive engine market. In the majority of cases, engine manufacturers produce most of the engine and assemble the engine. However, there are a several cases, like the CFM56 joint venture between General Electric and Snecma, and the Engine Alliance joint venture between General Electric and Pratt & Whitney, where a cooperative game is played between to competing engine manufacturers. In this case both parties make a binding agreement to cooperate by sharing technology and creating a joint product. Of interest in this research is the concept of noncooperative games which is indicative of the majority of cases in the market.

There exists specific rules when constructing games. Smit and Trigeorgis (2004) assert that *"following the rules of game theory can help reduce a complex strategic problem into a simple analytical structure consisting of four dimensions"*.

1. The players
2. The actions available to them
3. The timing of these actions
4. The payoff structure of each possible outcome.

There are two basic ways to formulate games and they are the *strategic* and the *extensive* forms. The next sections provide a taxonomy of games and equilibrium analyses.

3.2 A Taxonomy of Games

3.2.1 Strategic form

The strategic (or normal) form is a matrix representation of a simultaneous-move game. The definition of a strategic-form game is in terms of its constituent parts: players, strategies and preferences. The game is formulated in terms of a matrix where rows represent the strategies available to one player and the columns represent the strategies to another player. Each box (row/column combination) represents the payoffs to each player for every combination of strategies. These games are typically solved using the Nash Equilibrium concept discussed further in the next section. There are various ways to filter down the moves to determine the 'best' outcome.

The first approach to solving matrix games is through strategic dominance. Simply stated, strategic dominance occurs when one strategy is better than another strategy for one player, no matter how that players opponents may play. This is a first cut at eliminating strategies. There are two types of strategies, strictly or weakly dominant/dominated strategies. In mathematical terms, for any player i, a strategy $s* \in S_i$ weakly dominates another strategy if $s' \in S_i$ if

$$\forall s_{-i} \in S_{-i} \left[u_i \left(s*, s_{-i} \right) \geq u_i \left(s', s_{-i} \right) \right]$$

With at least one strict inequality. The S_{-i}represents the product of all strategy sets other than i's. On the other hand, s* strictly dominates s' if

$$\forall s_{-i} \in S_{-i} \left[u_i \left(s*, s_{-i} \right) > u_i \left(s', s_{-i} \right) \right]$$

A rational player would never play a dominated strategy. As a result of this premise, it is often possible to use dominance analysis to rule out some outcomes as possibilities when the game is played by rational players. It is often the case in some games that this leads to a unique prediction of the outcome when players are rational making this a dominance solvable game. Another way to view this concept is the idea that a dominated strategy is "never a best response" for that player, no matter his beliefs about the actions of his opponents.

If there is no clear solution using strategic dominance, another process exists to filter out strictly and weakly dominated strategies through a process known as Iterated Elimination of Dominated Strategies (IEDS) (Tirole, 1991). Figure 3.1 illustrates a payoff matrix where two players must choose simultaneously between their available choices of U,M, and D for player 1 and L,M, and R for player 2. For each payoff pair the first number is the payoff to player 1 and the second number after the comma is to player 2. At first glance, the maximum payoff possible to player 1 is 9, if player 1 selects choice D. However, player 2's maximum payoff is 8 when selecting choice R. If both players choose to stay with those choices, then player 1 will end up receiving a payoff of 2 and not 9. The choice of the *best* strategy is often masked by the complexity of the payoff scenarios that can occur. For this reason the process of IEDS facilitates the down-selection of choices in a rational manner.

The process of using IEDS begins by eliminating the dominated action M for player 2. With a reduced payoff matrix, actions M and D are dominated by U so they are eliminated. Finally player 2 does better by choosing action L than R (3 vs 2) so the equilibrium result is [U,L].

3.2.2 Extensive form

The extensive form game is often viewed as a decision tree. The main difference between the normal and extensive forms is the information that a player has regarding the actions taken

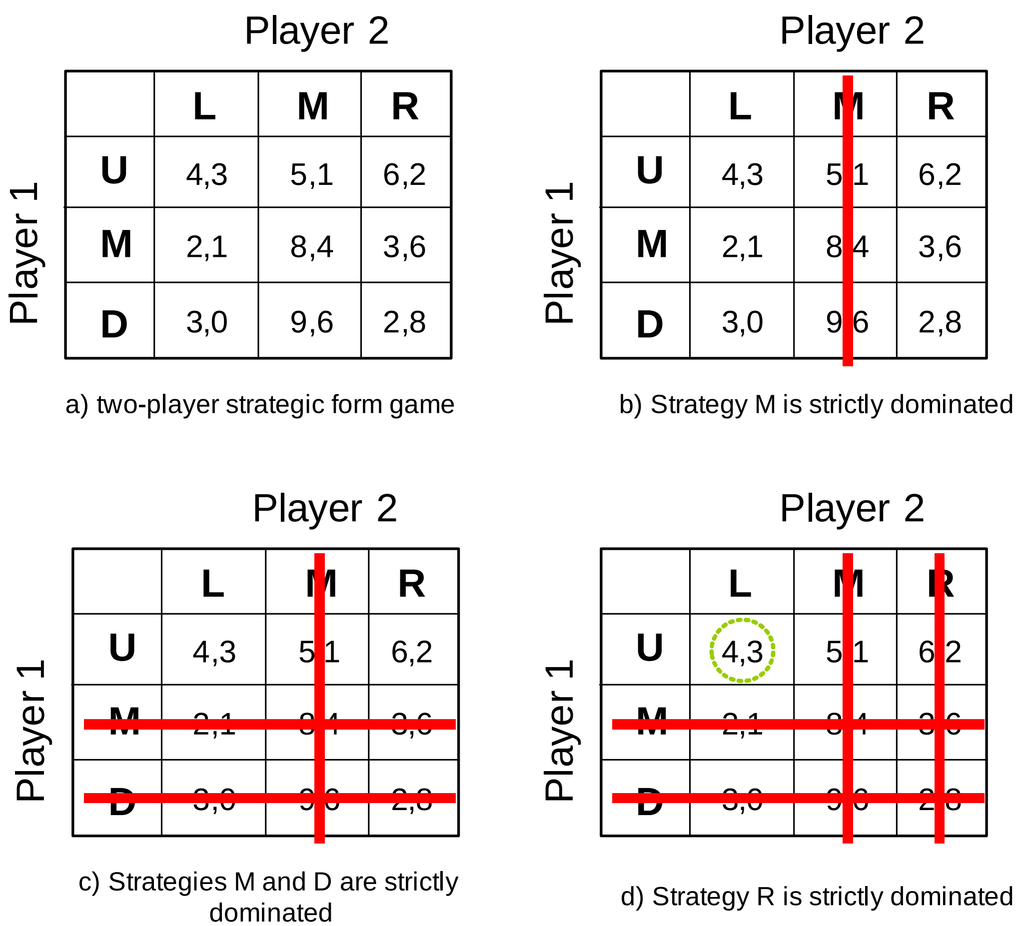

Figure 3.1: Iterated Strict Dominance (Tirole, 1991)

previously made. Extensive form game structures specify the order in which players make decisions. This is a valuable piece of information when formulating a strategy. At every point in time a player has a spectrum of moves available. A complete game can then be theoretically modeled from start to end. If the game model was extremely accurate, one could simply evaluate every possible combination of moves to determine the best possible sequence of decisions to guarantee victory. However, this is impossible due to large number of decision branches. Also, it is impossible to have perfect knowledge about all game parameters.

An example of a decision tree is shown in Figure 3.2 where two players have to make choices in quantity, q. Player 1 moves first with choices 3, 4 or 6 and player 2 then makes a choice with the same options. The resulting payoffs are shown at the bottom of the Figure where the first number is the payoff to player 1 and the second is the payoff to player 2. The

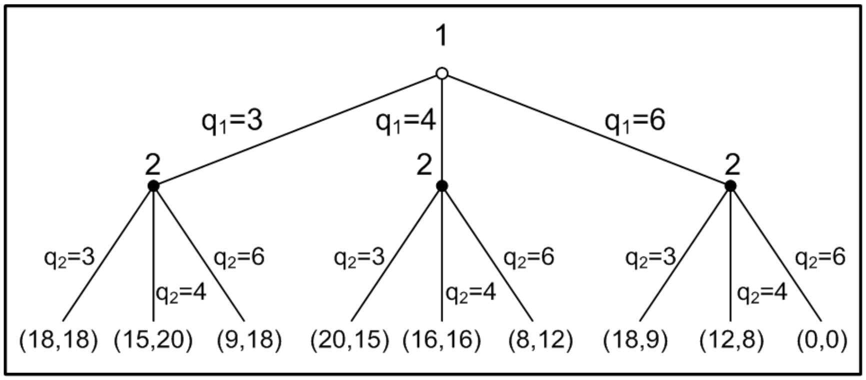

Figure 3.2: Extensive Form Game (Tirole, 1991)

outcome of the game depends on the information known to player 2. An information set for a player at a particular point in a game is the "set of decision nodes at which the player knows she is at but cannot distinguish without additional information" (Hazelrigg, 1996). For the game tree example in Figure 3.2, player 2's information set contains all three possible nodes which means that player 2 knows what choice in quantity player 1 has previously made. The information set concept is useful when modeling real world examples because more often than not firms cannot know *a priori* what decision had been made (or planned) by their competitors. To solve complex game trees there exists intelligent search methods that prune the tree branches to determine the equilibrium outcome of the game. The Alpha-beta pruning algorithm by Baudet (1978) was one well-known technique to solving complex game trees. Over the past decades there has been extensive work in this field to develop algorithms that are easy to implement and are fast and efficient in computing the equilibrium.

The framework developed in this research lends itself to a game tree analysis. But information-gathering capabilities are needed in order to create the specific information sets. The focus therefore, is on solving simultaneous games instead in a normal form structure.

3.3 The Nash Equilibrium

In game theory, a solution concept is a formal rule for predicting how the game will be played. The most commonly used solution concepts are equilibrium concepts, of which the Nash equilibrium (NE) is the most widely used.

> *"The Nash equilibrium is a profile of strategies such that each player's strategy is an optimal response to the other players' strategies"* (Fudenberg and Tirole, 1991)

Furthermore, no player has an incentive to deviate from his or her chosen strategy after considering an opponent's choice. Overall, an individual can receive no incremental benefit from changing actions, assuming other players remain constant in their strategies. There may exist more than one Nash equilibrium in a game. This solution concept can be viewed as a robust solution that minimizes the potential loss in payoff to each player.

A set of actions $\left(a_1^N, a_2^N\right)$ is a Nash equilibrium if the following conditions are met:

$$U_1\left(a_1^N, a_2^N\right) \geq U_1\left(a_1, a_2^N\right) \quad \text{for all } a_1\text{, and}$$

$$U_2\left(a_1^N, a_2^N\right) \geq U_2\left(a_1^N, a_2\right) \quad \text{for all } a_2$$

A set of actions is therefore a Nash equilibrium if each player cannot do better for herself by playing her Nash equilibrium actions given the other players play their Nash equilibrium actions. This problem can be solved by maximizing the utility functions of both players:

$$\underset{a_1}{max} U_1\left(a_1, a_2\right) \quad \text{and} \quad \underset{a_2}{max} U_2\left(a_1, a_2\right)$$

where each player takes each other's action as given. The optimization problem performs a search in the action space and determines iteratively if the conditions for a Nash equilibrium have been met. The process of iteratively eliminating strategies discussed in the previous section is common approach to solve simple games but when the action space is too large the solution must be carried out algebraically via differentiable equations in a system of two equations in two unknowns, $\left(a_1^N, a_2^N\right)$. A game solution can either result in a pure strategy or a mixed strategy equilibrium solution (discussed in the next subsection). A pure strategy is a deterministic description of exactly (100% certainty) what action the player will choose in a game (assuming they play rationally).

3.3.1 Mixed Strategies

Mixed strategy Nash equilibria result when players choose to play a pure strategy stochastically according to fixed probability distribution. A player with a mixed strategy randomizes between pure strategies. Nash (1950) showed that, if players are allowed to choose among their mixed strategies (players choose strategies randomly according to pre-assigned probabilities), then every n-player finite game contains an equilibrium solution. This result is very useful because it tells us that there is always an optimal outcome for each player in every game.

3.3.2 Pareto-Efficient Nash Equilibrium

In most complex games the outcome will result in more than one Nash equilibrium. One of the major challenges in this field is to determine which of the NE's to choose from. The problem with selecting an NE among many is that if both players do not agree on the same NE then the actions they choose are really not equilibrium actions at all which defeats the purpose of computing an equilibrium solution in the first place. The concept of a Pareto optimal Nash equilibrium has been widely studied to identify which of the NE's would be optimal to select from.

Two important refinements of the Nash equilibrium were established by Harsanyi and Selten to understand equilibrium solutions in games (Harsanyi and Selten, 1988). The first one relates to NE's that are payoff dominant or Pareto superior to all other Nash equilibria in that game. The second refers to NE's that are risk dominant where players will generally gravitate to a risk dominant strategy if they are more uncertain about the actions of other players. To best understand how to differentiate between these two types of equilibria the Stag-Hunt game example is shown in Figure 3.3. The game is also referred to as the

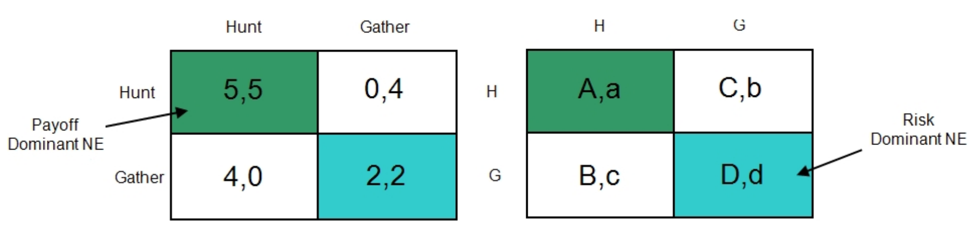

Figure 3.3: The Identification of Payoff and Risk-Dominant Equilibria in The Stag-Hunt Game

coordination game. Two players go hunting and they must choose to either hunt a stag (a deer) or hunt a hare. They each make a decision without knowing what they other chose.

If a player chooses to hunt a stag it requires the cooperation of his partner in order to be successful. A player can choose to hunt a hare by himself but it is also worth less than a stag. The payoffs associated with the different options are shown in the left matrix of Figure 3.3. If a player 1 chooses to hunt a stag but its partner (player 2) chooses instead to hunt a hare then player 1 receives 0 payoff and player 2 receives 4. Like the prisoner's dilemma, this game provides rationale as to why collective action might fail in the absence of credible commitments.

This game has two Nash equilibria. One at [H,H] and the other at [G,G]. The [H,H] is payoff dominant since it is the maximum the players can receive. However, there is the potential to lose a great deal and end up with a zero payoff. Therefore, the risk averse player would play the risk dominant NE at [G,G]. The formal description of these types of equilibria is as follows: [H,H] payoff dominates [G,G] if A≥D, a≥d, and at least one of the two is a strict inequality: A>D or a>d. Secondly, [G,G] risk dominates [H,H] if the product of the deviation losses is highest for [G,G] so that (C-D)(c-d)≥(B-A)(b-a). These are beneficial concepts that provide more clarity to equilibrium solutions.

3.4 Game Theory Software

There are several computer based decision software that use game theory to analyze complex games. The Maple© toolbox from MapleSoft© is used extensively by the mathematics community and can be implemented into the programming language platform MATLAB© to facilitate the modeling and of complex games. Another popular free game theory analysis tool is Gambit, developed by McKelvey et al. (1991). Gambit is a library of game theory software and tools for the construction and analysis of finite extensive and strategic games. Figure 3.4 is generated using the Gambit software. The software uses several search algorithms to compute the Nash equilibria. It can be used in either of two ways, as a graphical user interface (GUI) or as an integrated function within an algorithm. The GUI provides the user with options to iteratively eliminate solutions. Figure 3.5 illustrates the result of reducing a game via the IEDS method.

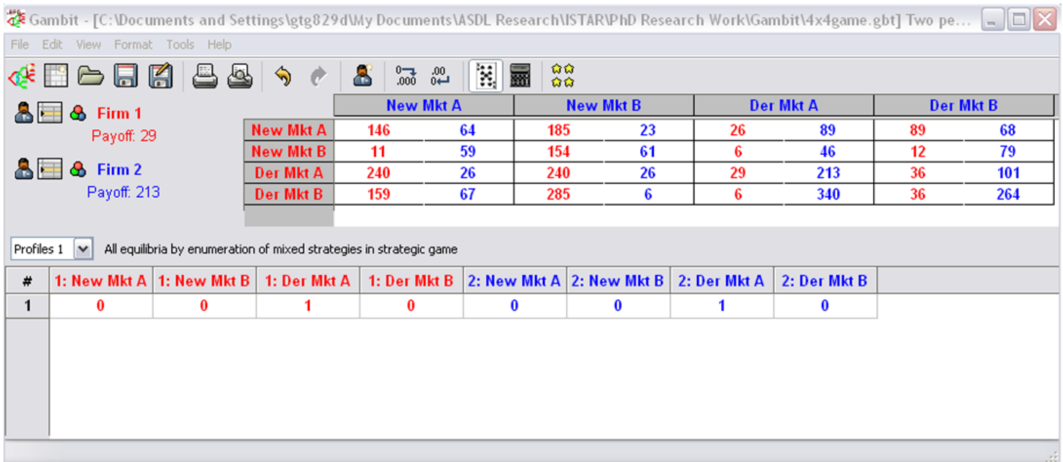

Figure 3.4: Normal-Form Game using the Gambit Software

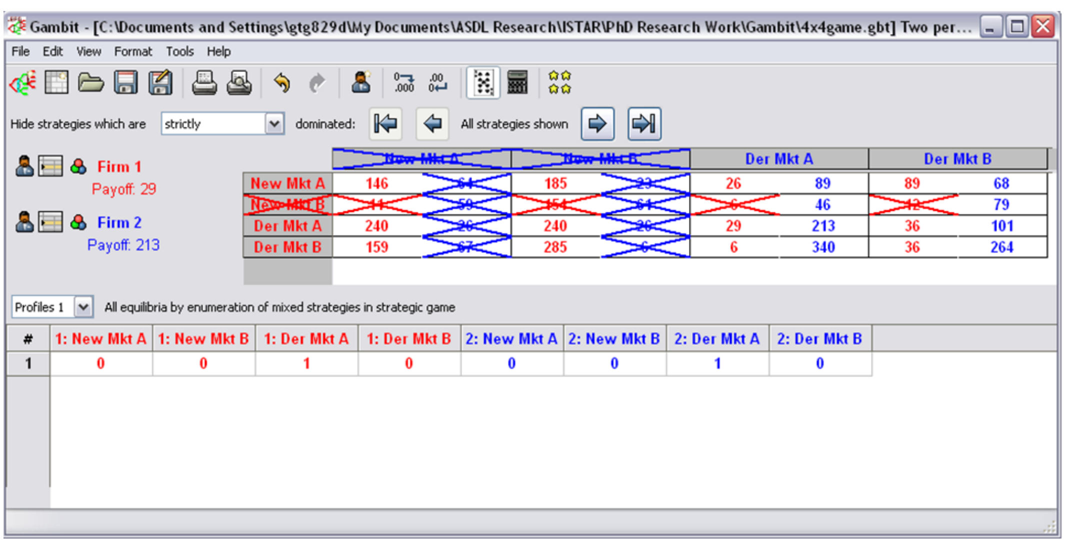

Figure 3.5: Elimination of Strategies using the Gambit Software

Chapter IV

FORMULATION OF A COMPETITIVE METHODOLOGY

The literature review in Chapter 2 outlined the pertinent processes and techniques that address conceptual design, decision-making and competitive analysis. This review demonstrated that there are several techniques that deal with decision-making in engineering but few that focus on market competition in the conceptual phase of design. Chapter 3 introduced game theoretic concepts and techniques that analyze competitive scenarios and have the potential to assist decision-making in the conceptual and preliminary phases of the design process. The current chapter proposes a methodology that borrows elements from advanced design methods outlined in the literature review and combines them with the competitive tools discussed in Chapter 3. The purpose of developing this methodology is to address the "gaps" within the specific research areas identified in Chapter 1.

This chapter begins by formalizing the questions presented at the end of Chapter 2 and proposing research hypotheses as guidance in the formulation of the research methodology. Figure 4.1 provides a visual linkage between the observations made in Chapter 1, the research questions and and the objectives in developing the methodology. The methodology will then be implemented using a commercial engine selection proof-of-concept in Chapter 5.

4.1 Research Questions and Hypotheses

Based on the literature survey and advanced design method identification it is evident that there is an emerging problem in systems conceptual design. In the commercial industry the success of products is driven predominately by market forces. Even for large scale systems like aircraft or aircraft engines the impact of the market can be significant. As societal demand and standards continue to increase, the design process of complex systems must become more sophisticated. In response to the design problems highlighted in current

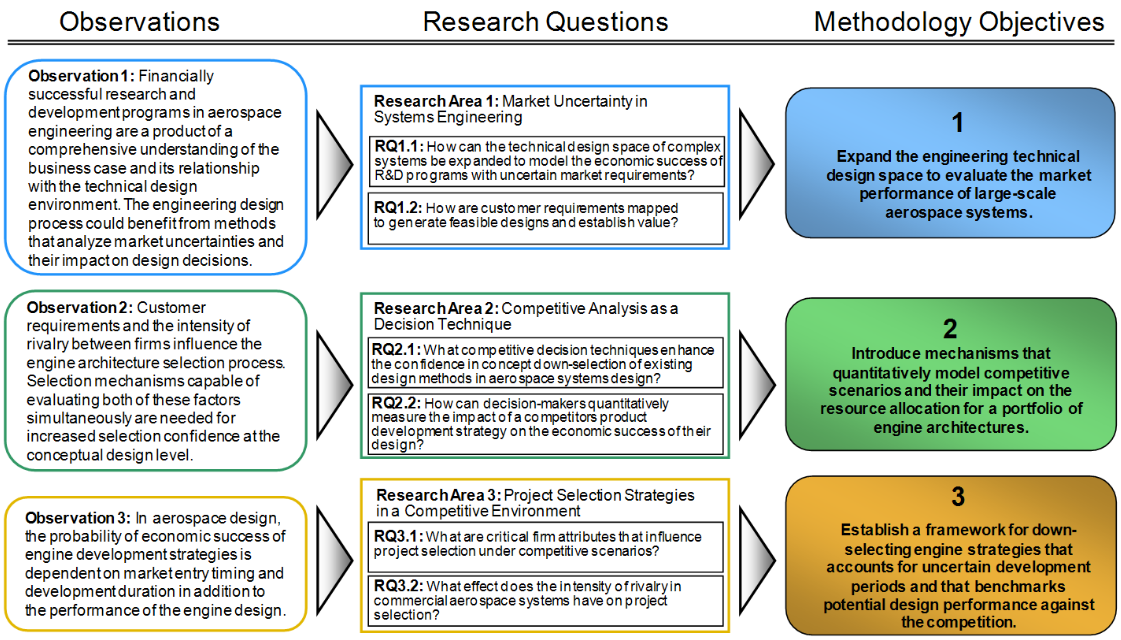

Figure 4.1: Recapitulation of Observations, Research Questions and Objectives

design processes a series of research questions are established as a means to guide the experimentation of the research. The three research objectives outlined in the first chapter narrowed the focus of the research into three overlapping areas (requirements and competition uncertainty, competitive analysis, project selection). They are now used as a means to establish formal research questions and propose a series of hypotheses that follow from the observations. These hypotheses will then be tested through a proposed process using the commercial aircraft engine selection problem as a proof of concept.

Chapters 2 and 3 identified certain advancements in systems conceptual design, competitive analysis and decision-making capabilities. However, these capabilities have not been integrated simultaneously into an integrated framework in order for designers to visualize the impact competitor moves might have on the success of their product. A significant challenge in the aerospace design community is the ability to model the economic impact of designs in a market. The first research area of interest focuses on better analyzing market requirements uncertainty and how that uncertainty propagates into the decision process in design. The idea is to incorporate decision variables that are indicative of the market performance of designs as part of the technical design space. Engine design for instance, would not only consist of choosing the optimum settings of thrust, engine weight, fuel burn, technologies, etc. but also how much market share that design achieves, what type of return on investment it has etc. The first two research questions are posed in an effort to develop this type of environment.

> **Research Question 1.1:** How can the technical design space of complex systems be expanded to model the economic success of R&D programs with uncertain market requirements?
>
> **Research Question 1.2:** How are customer requirements mapped to generate feasible designs and establish value?

These research questions address the first objective which is to create a means to expand the technical design space to include competitor influence. They refer to the need for a thorough analysis of the market competition at the technical level in conceptual design. The focus here is to go beyond the capabilities of current simulation environments and investigate the effects of factors not specific to the design but that still influence the final design selection. For example, fluctuations in engine material or labor costs are likely to impact the cost of maintenance and can alter the trade-offs made with other metrics like takeoff performance or mission range.

The second question specifically seeks to find out how to incorporate market requirements composed of different "customer profiles" and map them to other metrics in the design space. These requirements can be derived from different market segments with characteristics such as missions with high or low payload/range requirements or hot and high altitude take-off performance requirements.

In order to answer these questions, a solution path can be guided by establishing a formal hypothesis that can then be tested by applying it with a proof-of-concept. The advanced design methods described in section 2.2 combined with the computational power and fidelity of a modeling and simulation environment provide a solid foundation for the development of a methodology that can address the first two research questions. This claim can be formalized as the first hypothesis.

Hypothesis 1: The uncertainty of market requirements and competition can be quantified within a single unified environment that synthesizes the business case of customer requirements with the performance metrics of designs.

Since the focus of this research is on competitive analysis as it pertains to conceptual design selection the second research area looks into analyzing competitive uncertainty in different types of markets. It was observed that research and development programs that generate commercial products are very sensitive to market forces. Current design methods in engineering can benefit from this market knowledge if it considered early in design. This will help mitigate the risk of uncertain market performance. Chapter 3 provided a broad investigation into the field of game theory and techniques that can assist in analyzing uncertainty due to competitive product positioning. The second set of research questions seek to discover ways to incorporate these techniques into aerospace engineering.

Research Question 2.1: What competitive decision techniques enhance the confidence in concept down-selection of existing design methods in aerospace systems design?

Research Question 2.2: How can decision-makers quantitatively measure the impact of a competitors product development strategy on the economic success of their design?

As mentioned earlier in Chapters 1 and 2, competitive analysis in conceptual design has relied on subjective and qualitative reasoning based on intangible criteria that is difficult to model at the conceptual level. The goal here is to identify a means to quantitatively represent the impact of a competitors' move on a design strategy at the conceptual level.

In order to carry out a competitive analysis using the various advanced design techniques, the design problem should be converted into an equivalent problem in terms of a game structure. The challenge here is to maintain the same or similar conceptual design decision criteria such as thrust, engine weight, fuel consumption (for engine design) and additionally introduce market criteria like competitor payoff, market share, so on and so forth. A process is needed to allow designers to combine these metrics without introducing unmanageable uncertainty or variability. This hypothesis states that is is possible to use game structures to represent a competitive decision-making problem without removing the technical metrics of the design problem.

> **Hypothesis 2:** Through the use of game theoretic techniques decision-makers can construct a systematic game-based methodology that enhances the design down-selection confidence and mitigates the potential of financial risk.

Within the investigation of game theoretic techniques, a sub-goal will be to determine which techniques are most efficient in identifying robust competitive solutions.

The third set of research questions are meant to help facilitate the design selection process by investigating different product strategies. The structure of the research questions and hypotheses make it so that they build on each other. Therefore, by implementing the methodology proposed via Hypothesis 1 with the mechanisms to evaluate competitive uncertainty in Hypothesis 2 we can study the project selection opportunities under the effects of different competitive scenarios. The main effort here is to test how different firm characteristics can influence the selection of a project and what effect one firm's development attributes has on another firms' project selection strategy. For instance, one firm may be more efficient at developing a modified product by leveraging technologies from an older product and can therefore potentially gain from entering the market sooner. Conversely, another firm may have an advantage in developing new products and although it may likely not enter the market prior to the first firm, it can still potentially gain more market share based on its new design performance. These are scenarios that are of interest and can be posed through a third set of research questions.

> **Research Question 3.1:** What are critical firm attributes that influence project selection under competitive scenarios?

> **Research Question 3.2:** What effect does the intensity of rivalry in commercial aerospace systems have on project selection?

The review of R&D project selection in Chapter 2 provided an extensive taxonomy of selection studies in both the economics and management fields. These studies produced selection models that had firms selecting a single project versus a portfolio of projects where two or more innovations were considered simultaneously. They also considered single stage selection versus multi-stage selection where the latter allows the firm to reallocate resources to other projects at the end of each stage. These models as described in Chapter 2 are beneficial to the development of a project selection framework for aerospace design but do not have the depth needed to analyze the complex uncertainties of aerospace systems. However, in these models in conjunction with advanced probabilistic methods and a well-established modeling and simulation environment can provide practical down-selection capabilities in the design process. These thoughts are formalized into the third hypothesis.

> **Hypothesis 3:** Project development strategies can be formulated using probabilistic techniques in conceptual design thus recommending robust market entry opportunities and optimal project portfolio selection.

Finally, it is hypothesized that the well-established mathematical branch of game theory will enable competitive modeling and provide a rational selection of strategies in systems design. Each hypothesis is meant to build on the previous one. In order to test these hypotheses a method must be developed that includes the techniques described. Presented below is an overarching hypothesis which combines the three hypotheses to establish the main theme in this dissertation:

> **Overarching Hypothesis:** A game-based strategy exploration method that employs game theoretic and probabilistic analysis techniques facilitates the systematic exploration and selection of architectures under uncertain competitive scenarios.

This section is summarized below in Figure 4.2 where the research questions are mapped together with the hypotheses.

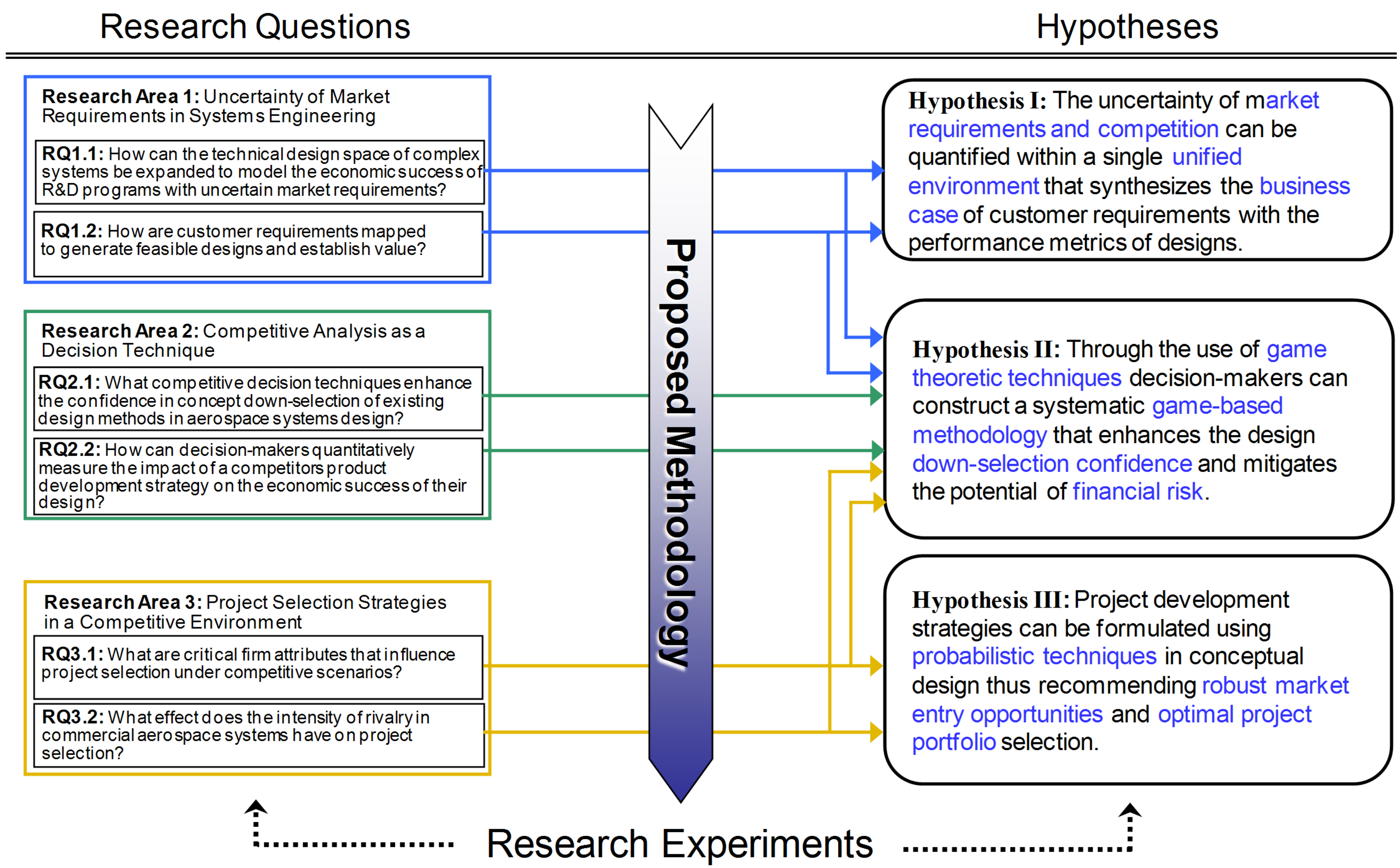

Figure 4.2: Hypotheses Mapping with Research Questions

4.2 A Proposed Methodology for Competitive Design

The research questions and hypotheses in the previous section were established to guide the development of a systematic process to analyze complex systems in a competitive environment. This process, which results from the synthesis of enabling techniques and methods from Chapters 2 and 3, is proposed as a five-step methodology that addresses the need for a structured approach to bridge the gaps identified in 2.6. It is then implemented through a proof-of-concept based on a commercial engine selection problem in Chapter 5. This methodology is illustrated in Figure 4.3. The methodology is first tested on a base-case model and then fully implemented on the proof-of-concept in Chapter 5. Steps 2 and 3 are primarily associated with the generation of design alternatives and their evaluation in terms of technical performance, customer value, etc. The focus in these two steps reside in the synthesis of analysis codes to generate and evaluate these alternatives. Steps 4 and 5 are directly associated with analyzing the competition and strategically selecting R&D projects. The approach taken by the author to build this methodology was to first create a base-case model of steps 4 and 5 with notional projects to test the competitive analysis method. Steps 2 and 3 are then added in the proof-of-concept study to provide more project analysis resolution and flexibility in the design space. In this chapter, the base-case model and its notional results are presented alongside the explanation of each step.

The sequence of steps in the methodology were formulated with the Integrated Product and Process Development framework in mind (section 2.2.1). The purpose of each step is to capture the goals of the three research areas described in the introduction and illustrated in Figure 4.2. Throughout the description of each step in this section, the reader will be referred back to the research questions and hypotheses.

4.2.1 Defining the Project Selection Problem (Step 1)

In most engineering conceptual design processes the first step involves defining the problem. While this is often considered the first step in most design processes, in reality, the *original* problem is constantly being defined and updated throughout the entire design process, from

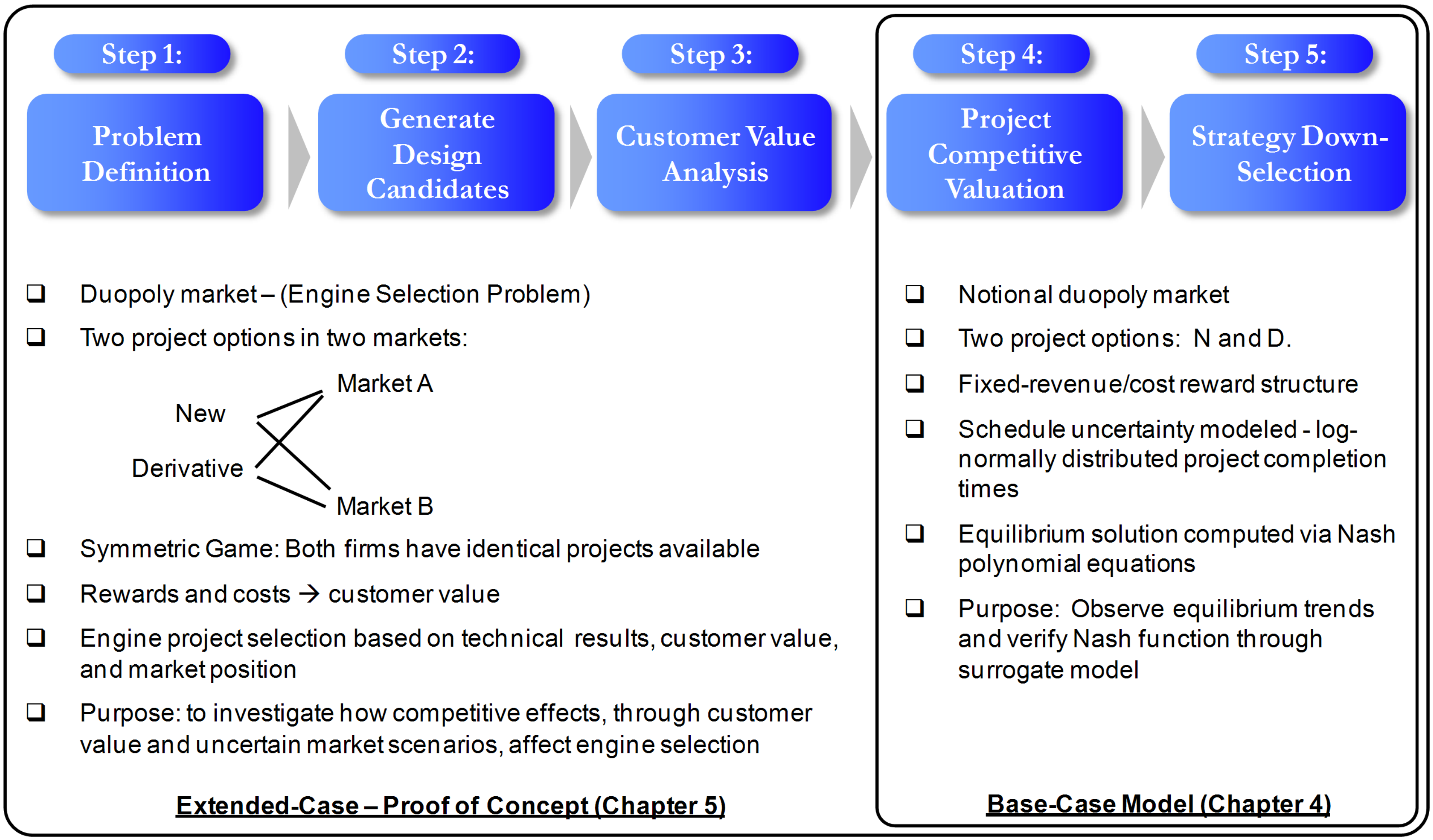

Figure 4.3: Proposed Five-Step Methodology for Analysis of Competitive Designs with Modeling Assumptions

conceptual design to detail design and then through manufacturing and production. Many design processes have a significant level of feedback that helps refine the problem and thus more accurately match the final product with the problem requirements and expectations. The idea of consistently verifying design accuracy throughout the process is beneficial when product requirements are likely to deviate from the original definitions. Defining the problem is usually the most critical step in the process and yet its importance is often overlooked due in part because it requires the least amount of time out of all the steps in the process to accomplish.

Defining the problem of an engineering endeavor can be carried out in many different ways. Generally, this process begins with identifying the need for a product. Oftentimes, the business development and marketing departments will make an assessment of the market and their business objectives to determine what opportunities exist in order to be profitable. Systems engineering also has a similar approach called the "pre-concept exploratory research stage" (Fossnes and Forsberg, 2006) where performing a variety of research studies often leads to the development of innovative ideas and technological capabilities which are then the seeds to the initiation of a new project. More often than not a need is established in response to a customer identifying a shortcoming in their existing system or capability and request an upgrade or new solution. An airline for example, may want to expand their services to take advantage of an emerging market that consists of a long distance, high capacity city-pair but realize that existing aircraft have a limited payload and range capability and cannot satisfy that market requirement. Airlines are always seeking to minimize their operating costs and there are frequent demands to manufacturers to produce fuel-efficient aircraft with engines that are capable of meeting future noise and emissions standards while still increasing payload capacity and range. Military systems have performance requirements that are usually defined by their goals to fly faster, carry more ammunition, become less detectable, etc. Although military systems have strict performance goals, the solution space is more open-ended than their commercial counterparts mainly because of the tight regulatory requirements that commercial systems must satisfy. Both however, share increasingly significant economic constraints that are of vital importance in the conceptual design phase.

The selection of the project to pursue for design and development must be consistent with the business goals outlined in the business case. The creation of a business plan to meet the stakeholders' needs usually takes place with upper-level management since they have the capabilities and resources to convince the customer that their product can satisfy their needs. Activities that involve market research and identification of profitable opportunities in specific market segments are conducted during the development of the business case. The problem of choosing a development project among a portfolio of projects consistent with the business goals is analogous to the problem definition of most conceptual design processes with some added prerequisites. A thorough analysis of these market opportunities and scenarios must occur in conjunction with the system performance analysis so each design can be evaluated based on, not only its technical merits, but its economic viability and competitive potential.

In the next section, a description of the project roadmap is introduced. This is the first task that describes how different R&D investment opportunities are analyzed based on various market scenarios. The purpose here is to bound the competitive problem and avoid getting lost in the complexities of market forces which extends beyond the scope of this research.

4.2.1.1 Defining a Project Selection Roadmap

The methodology developed in this research begins with the specification of a project selection roadmap. The purpose of this roadmap is to determine the applicable scope of the methodology to R&D project selection problems. It is precisely at the very beginning of the process where the key product and process characteristics must be identified to best translate the customer requirements to the engineering characteristics. One of the advantages of laying out a project selection roadmap is to bound the problem. It specifies the type of market scenarios and investment opportunities that can be analyzed. This allows the methodology to focus on specific examples and therefore provide a useful experimental process. Since this research is motivated by the commercial aircraft engine selection problem, this becomes the proof-of-concept for the methodology. The characteristics of this problem

		Alternatives		
Game Structure Attributes	Number of Players	Single (Decision Theory)	Two	N-players
	Available Actions (Type of Project)	Single	Sequence of Projects	Portfolio of Projects
	Information Set	Perfect Information	Incomplete Information	
	Number of Game Stages	One-Stage	Two-Stage	Multi-Stage
	Order of Play (Timing of Investments)	Sequential	Simultaneous	
	Analysis of Equilibria	Pure Strategies	Mixed Strategies	

Figure 4.4: Game Structure Matrix of Alternatives (MoA)

are used in part to define the project selection roadmap.

The review of the project selection literature in section 2.4 provided a highlight of the spectrum of work done in the economic and strategic management fields. That information is used here to establish the third research focus area: *Project Selection Strategies in a Competitive Environment* (Figure 4.2) and is also used to formulate the project selection roadmap. There are many competitive situations that exist in many different types of R&D investments. If one were to map all these together the result would a list of millions of project selection roadmaps. Each roadmap would be derived by combining different options of project alternatives, customer requirements, market attributes, and competition attributes. A useful to technique to visualize and down-select an appropriate roadmap is the Morphological analysis (developed by Zwicky (1948)) . This technique begins with the creation of a Matrix of Alternatives (MoA).

Figure 4.4 illustrates a matrix of alternatives which displays the alternatives for the game structure attributes. The highlighted alternatives are selected to form the game structure for this proof-of-concept. There are *two* engine firms and each has a *portfolio of project*s to choose from for research and development. Both firms have *perfect information* about the game. Each knows exactly the payoffs available to the other. The game will be played in *one stage* where both firms will only have one opportunity to make a project selection decision. The first stage is referred to as the research and development stage whereas subsequent stages involve commercialization of the product. Smit and Trigeorgis (2004) show how a two-stage R&D game is constructed under demand uncertainty assuming a duopoly market structure. Each of the two competitors makes a decision to determine if and when to make an R&D investment (1st stage) as well as decisions regarding follow-on commercialization of the investment (2nd stage). They further state that the type of competition in each stage will affect the equilibrium production and optimal investment strategy. The objective in this research is to observe how competition affects R&D investment decisions since commercialization of aircraft engines depends less on the design of the engine and more on the way they are marketed. Multi-stage games introduce a larger challenge in constructing the game as well as analyzing the equilibrium results.

Both firms select their project choice *simultaneously* and cannot know *a priori* what the project the other has chosen. In a real competitive scenario between firms the game would be sequential where firms choose their project based on the knowledge of having seen their competitor's choice. However, the analysis of game decision trees is more complex and is beyond the scope of this research. The analysis is made based on pure strategies only. The subject of mixed-strategies is introduced in this research but is not studied in the proof-of-concept. The subject of equilibrium analysis is presented in step 5 of the methodology. The purpose here is simply to establish the outline of the game to be played.

The rows of the matrix correspond to the different categories associated with competitive project selection problems. Each column is an alternative solution option to each category. The total number of possible combinations is calculated by multiplying the alternatives together for each category. For example, the matrix in Figure 4.4, contains 243 possible game structures that can be analyzed. Another important point to mention here is that the level of complexity in the roadmap increases with certain alternative choices.

The morphological analysis is repeated three more times for the three remaining areas: project alternatives, customer requirements and market attributes.The market scenario options are based on the requirements gathered from the market and customers. This task involves generating different plausible competitive scenarios that effectively bound the uncertainty of the project selection problem.

Prior to conducting those morphological analyses a QFD analysis is conducted on the customer requirements. For the commercial aviation case, the customers are the airlines and

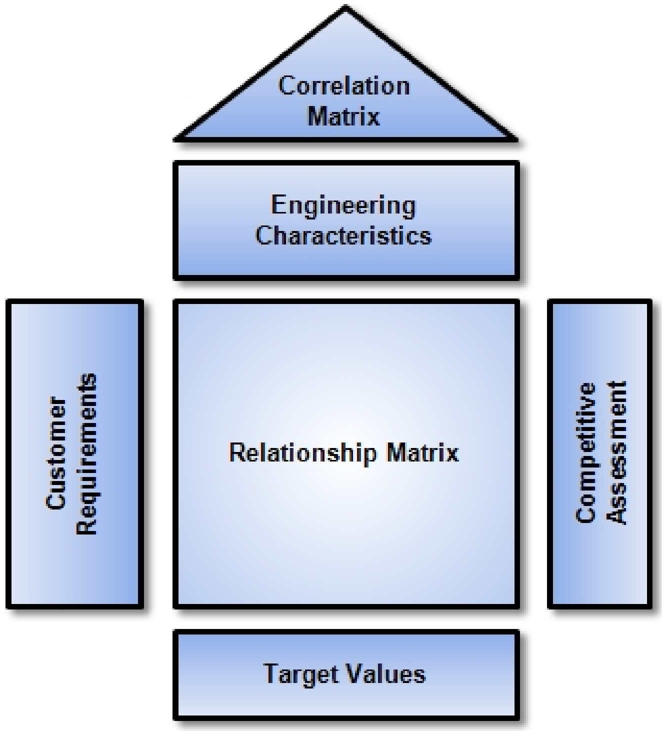

Figure 4.5: The House of Quality for QFD

they seek to purchase (or lease) an airframe/engine combination for their fleet. The QFD analysis begins by listing the customer requirements that have been gathered by the design team into rows (see Figure 4.5). These are also referred to as the "voice of the customer". The engineering characteristics are then identified and listed in columns. These are metrics that will be used to help satisfy the customer requirements. The relationship matrix in the middle of the House of Quality specifies the degree of inter-relationship between the customer requirements and the engineering characteristics. A nonlinear scale is used to determine the weight of importance between the requirements and characteristics. The correlation matrix or "roof" of the House of Quality identifies the degree of interdependence among the engineering characteristics. A competitive assessment can be performed by benchmarking each engineering characteristic of the product against other competitor's similar products. The result of the QFD process is a document loaded with information that is continuously updated throughout the design process. It serves as a planning tool to determine which engineering characteristics are most sensitive to the requirements and enables designers identify the appropriate processes needed to satisfy these requirements. The QFD is utilized in this methodology in step one to identify the key customer requirements and characteristics of the commercial aircraft/engine market. The details of the implementation will be discussed in Chapter 5. The information from the QFD is used to populate the customer requirements matrix of alternatives.

The market scenarios matrix of alternatives is created with the functional categories representing player (manufacturing company) attributes. For example, one attribute can be the relative efficiency of a player in completing a specific type of project compared to another player. In the aerospace community, this is analogous to one manufacturing company having a faster time-to-market for a specific type of aircraft than another manufacturing company. The term *efficiency* here is defined solely in terms of the speed of a project's development. The main purpose of developing scenarios is to reflect a variety of potential future competitive situations. In deciding between several projects to research and develop, a company will want to evaluate each project against possible competitive circumstances that may arise. Fahey and Randall (1997) and Ahmed et al. (2003) suggest generating a best and worst case scenario as well as several likely scenarios that fall somewhere in between.

The third and final matrix of alternatives is created for the project alternatives. For commercial aircraft engine development projects, example categories could be the type engine, where possible alternatives are *new* or *derivative* engine architecture. These categories would typically represent physical characteristics of the engine like cycle parameters, mechanical component designs, technology options, etc.

The final task in this first step is to integrate the game structure, the market scenarios, the customer requirements, and the project alternatives into a project selection roadmap. The information from each matrix is fed into the project selection problem throughout the methodology as shown in Figure 4.6.

To recapitulate, a project selection problem must be fully described in order to proceed with subsequent steps. This will facilitate the analysis of results. A summary of this step is presented in Figure 4.7.

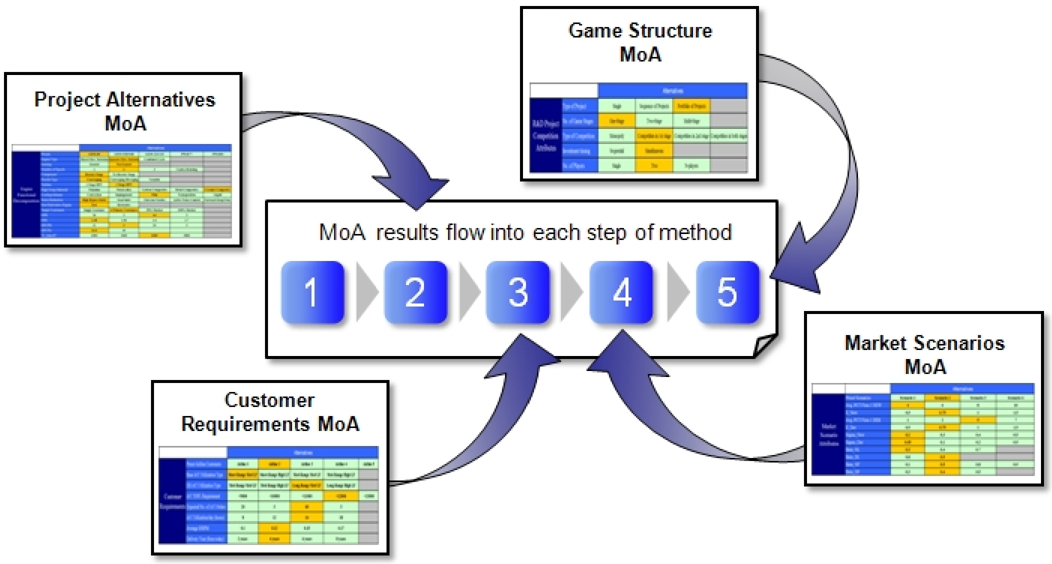

Figure 4.6: Step 1: Integration of MoA's into Project Selection Roadmap

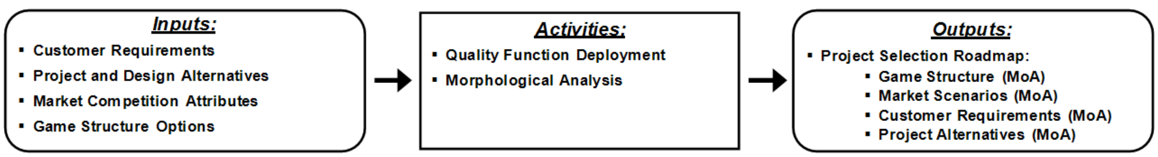

Figure 4.7: Step 1 Summary of Activities

4.2.2 Generation of Design Candidates (Step 2)

4.2.2.1 Task 1: Map Customer Requirements

After having defined the problem and specified a project roadmap in step 1, the next step is to develop a way of evaluating different alternative designs with the intention of eventually selecting the best one. Prior to generating said designs for each project, it is necessary to identify what metrics will be used to compare them against each other. These metrics represent measures of value to the customer.

Customer requirements can be traced back to specific metrics like performance, time, cost and quality. Performance is a measure of how well the design is meeting its operative goals. The time dimension refers to any aspect of time associated with the design. For most consumer products, the time-to-market metric has a significant impact on the overall value of the design to the customer. Perhaps the most important deciding factor in customer requirements is cost. The cost metric refers to any monetary aspect of the design. The concept of quality is more complex than other metrics since it is a characteristic that can be defined in many ways but it is essentially related to how well the product satisfies the customer's criteria.

Beyond these four fundamental customer metrics there is the concept of value which is a more inclusive measure of a customer's desires. Value can be viewed as the worth of a product and is sometimes computed by dividing a product's quality by its cost. Throughout this research, the term customer value expresses the total worth of a particular system or design to a customer. Worth is a relative measure of how closely the design matches the customer's requirements. In many aerospace engineering systems, the benefit-to-cost ratio is an common measure of customer value.

There are various managerial tools that assist decision-makers with analyzing customer requirements. The Seven Management and Planning Tools, part of the Total Quality Management concept, is a set set of techniques that facilitate the brainstorming process of decomposing vague concepts into manageable parts. The most commonly used in systems engineering are the Affinity and Cause/Effect diagrams and the Interrelationship digraphs (Leonard, 1999). The House of Quality is also a common graphical technique as part of the Quality Function Deployment process (Matzler and Hinterhuber, 1998).

To summarize, the mapping of customer requirements is a top-down process that specifies what value metrics are necessary for each requirement, what attributes best describe the value metrics and what design alternatives best match the attributes, metrics, requirements, so on and so forth. Figure 4.8 shows how this mapping fits in with the rest of the methodology. In Chapter 5, each aspect of the requirements mapping will be described in detail. There will also be an explicit description of the assumptions made in this mapping process.

4.2.2.2 Task 2: Create Design Space

There are several ways to generate potential alternative designs or concepts. Each process is unique to the problem they are attempting to generate solutions for. In many cases, exploring ideas through brainstorming is a popular approach. These can take place within

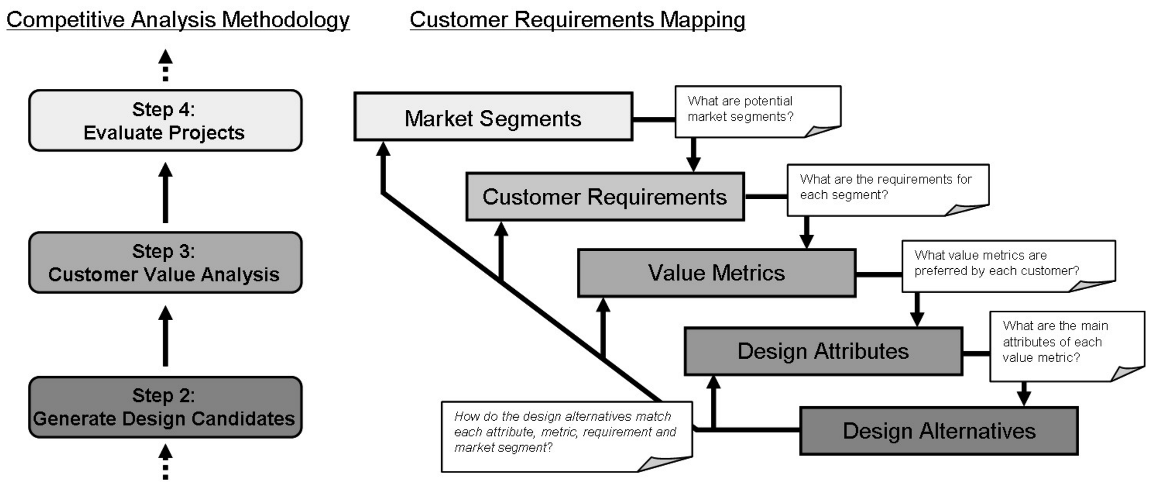

Figure 4.8: A Top-Down/Bottom-Up Mapping of Requirements

an integrated product design team (IPT) or individually. In aerospace engineering however, design problems tend to be very complex to simply brainstorm potential solutions for. Engineers usually will suggest ideas that can be described qualitatively but also carry out a conceptual decomposition of the problem to better formulate alternative solutions.

The first step is to decompose the problem into smaller parts or functions. Functional decomposition can be described as translating the design problem in terms of a flow of energy, material and information (Dieter, 2000). This is beneficial to the engineer in knowing what purpose the design serves. This is analogous to the *customer whats* of the QFD. Design concepts, or the *hows*, are then generated via numerous methods. Physical design parameters for instance, like length and weight, and material properties can describe a product's primary attributes. These are characteristic functions of possible system. A Morphological analysis helps to map all the functions into categories and suggest alternatives for each function. Combining an alternative from each function is a way of formulating a potential concept. As a result, a morphological matrix can define the alternative design space.

With the advent of fast computation capabilities and high fidelity analysis tools a physics-based design simulation environment provides a means of generating concepts based on the parameter boundaries established in the morphological analysis. Most companies have developed modeling and simulation (M&S) environments in-house to perform design trades and generate feasible concept alternatives. Particularly in aerospace engineering, the need for physics-based analysis tools is paramount to the development of feasible design solutions. The ability to quantitatively assess alternatives with respect to a physical set of requirements is critical in any decision-making process. This is most commonly achieved through an M&S environment.

The modeling and simulation of aerospace design problems typically consists of a series of disciplinary sizing and synthesis tools that, when combined together, are able to generate a wide variety of design concepts. The linkage between these analysis tools and models must be well defined in this step. Design parameters that will be varied in the simulation process are also identified in this step. Fast and efficient computation capabilities have expedited the process of generating a wide range of concepts with M&S environments. These environments produce a parametric design space that can be used to analyze a wide range of design configurations and quickly observe the quantitative impact of design changes on the economic requirements of a system. They also provide a platform for supporting robust design simulation and probabilistic analysis. These environments tend to be very specific to the design problem being analyzed. A detailed explanation of the M&S environment used in this research is presented in Chapter 5 for the proof-of-concept. Step 2 is summarized in Figure 4.9.

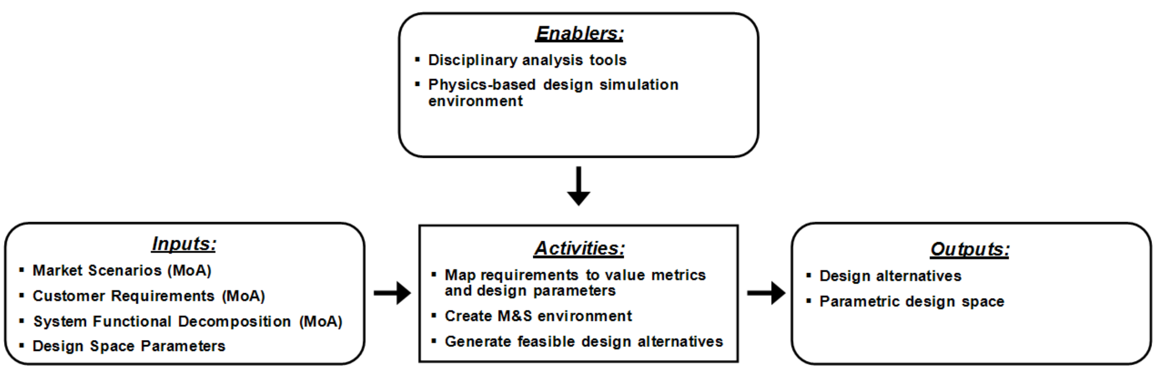

Figure 4.9: Step 2 Summary of Activities

4.2.3 Evaluating Customer Requirements (Step 3)

In step 2, a modeling and simulation environment was created to generate feasible design alternatives that are line with the market scenarios and customer requirements. The objective of step 3 is to evaluate these designs against the customer value metrics (criteria) identified in step 2, create a method of assigning a *value* to each design, and rank them based on how well they meet those criteria. In looking forward to step 4, assigning a value to each design alternative helps categorize the designs based on market segments and customer requirements. Since each project contains different alternative designs, it is beneficial to know how these designs rank within each project and it also facilitates the down-selection of both projects and designs in step 5.

4.2.3.1 Task 1: Multiple Criteria Design Valuation

Most complex systems design problems involve selecting alternative designs based on a finite number of choices and performance criteria. The selection process can be carried out by either selecting the most favorable design from the set of alternatives or ranking them based on the criteria. There is a wide range of multi-attribute decision making (MADM) methods that combine both qualitative and quantitative data together to assist the down-selection of designs (Sen and Yang, 1998).

The customer value analysis in this methodology takes place within the modeling and simulation environment. After generating alternative designs in step 2, each design is then automatically fed into a customer value calculation model that takes each design through a series of revenue and cost models to evaluate the design. Each design is then given a value based on how well it performed for all the customer attributes and is ranked among the other candidate designs. A finite set of representative attributes that are most important to the customer are selected *a priori* to evaluate each design alternative. The final value, in the form of an overall evaluation criterion (OEC), is a function of these attributes. This function is shown in equation 4.1.

$$F(x) = \sum_{i=1}^{n} w_i f_i(x) \tag{4.1}$$

Where $f(x)$ is the of value of the criteria (attribute) for each alternative design and w_i

is the weight of that criteria. For each attribute, a normalized value of $f(x)$ can also be computed by specifying minimum and maximum values for the attribute and what target is desirable (to minimize or maximize said attribute).

For the purposes of this research and the proof-of-concept application in Chapter 5 an OEC is used as the customer value ranking and selection method. Employing an OEC as a MADM method can often be over-simplistic and lead to sub-optimal results compared to techniques like Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981) and Analytic Hierarchy Process (AHP) (Saaty, 1990). The main disadvantage occurs with the estimating the importance weights for each normalized attribute. They are often estimated based on a consensus within a design team. For a small number of customer attributes however, the OEC approach is beneficial. This type of simple-weighted method facilitates the automation process of rapidly computing the customer values for each design. It is also easy to implement in a wide-range of problems. For real-world applications that involve more customer value attributes and also necessitates better accuracy for customer value selection, the design engineer can replace the OEC method and employ other types of MADM techniques. The M&S environment can be considered as a plug-and-play platform with the steps in the methodology remaining the same. A full description of the OEC approach taken in this research is described in step 3 of the proof-of-concept in Chapter 5. A summary of step 3 is illustrated in Figure 4.10.

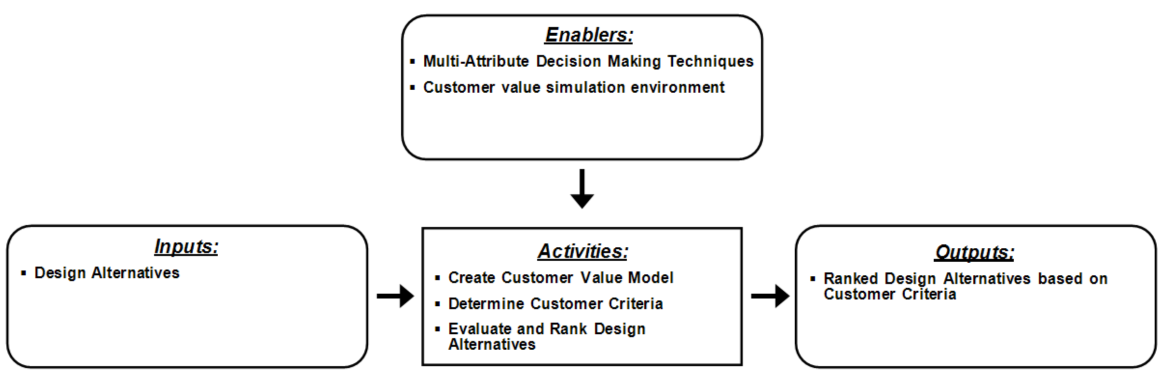

Figure 4.10: Step 3 Summary of Activities

4.2.4 Project Evaluation (Step 4)

After having established a modeling and simulation environment to generate design alternatives and a customer value model to evaluate and rank those alternatives, the methodology now proceeds with a competitive analysis of these design alternatives. The reader is referred back to Figure 4.6 which shows how a project roadmap was generated. The project roadmap serves to guide the competitive process through a game structure and assist the competitive calculations.

4.2.4.1 Project Structure

The literature review of the project selection problem in section 2.4 showed that there exists a myriad of ways of selecting R&D projects. The purpose of that review was to carve out and define the scope of this research by establishing criteria that was consistent with the commercial aircraft engine selection problem.

Selecting a commercial aircraft engine for development can be viewed as an R&D project selection problem. This aircraft engine industry is characterized by a handful of players, usually two to three large engine manufacturers, that have to design, develop, and produce gas turbine engines to compete in a global arena where there is uncertain development and reward levels. The game-based model developed to characterize this project selection problem builds on the work done by Loury (1979) and Ali et al. (1993). Their efforts provide a working foundation for this research since they "*model the new product development process as the simultaneous consideration of different types of projects in a rivalrous market with explicit representation of technical uncertainties associated with different projects and firms' asymmetric efficiencies in completing projects*" (Ali et al., 1993). Whereas their work uses fixed rewards, the interest in this research is to investigate how variations in customer value impact the selection process of aircraft engine development projects. Additionally, their efforts assume project cost to be fixed while the proposed methodology in this research utilizes a discounted cash flow (DCF) analysis that calculates cost and revenue directly as a function of project performance and customer requirements. An important assumption made in those efforts as well as in this research is that once a firm undertakes a given product

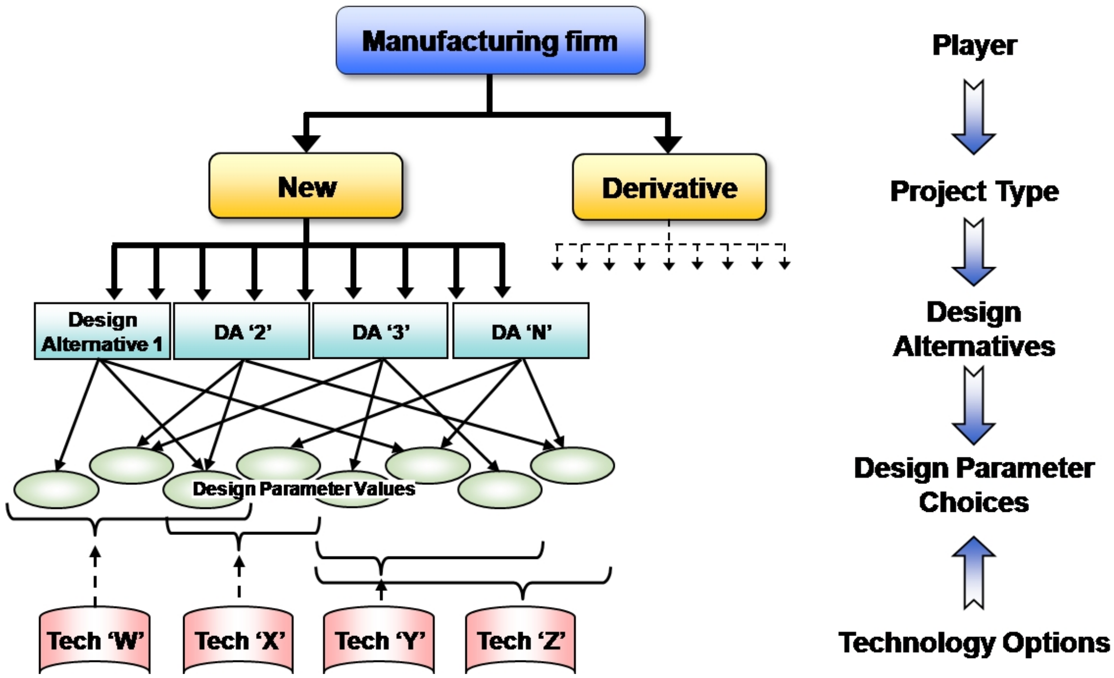

Figure 4.11: Hierarchic Project Mapping with Design Alternatives

development there is an irrevocable commitment of resources. This is consistent with the aircraft and engine design philosophy which affirms that cost-committed at the outset of the design increases as the development progresses.

Before continuing with the game structure development, an understanding of the linkage between project types, design alternatives and design parameter choices is warranted. Keeping the engine selection problem in mind, an engine manufacturing firm, one of two or three players in the market, has a project portfolio of various types of development projects to choose from that leads to a product (engine) for sale in the market. There exists two types of projects; a new (innovative) project or a derivative (modified) project. Each project type encompasses a parametric design space with many possible design alternative solutions. These design alternatives are constructed by selecting a combination of key design parameters. In many cases, the selection of design parameters will be driven by enabling technologies. The hierarchy of this project decomposition is illustrated in Figure 4.11.

It is important to note here that the project identification process, particularly the development of the parametric design space for the design alternatives, takes place in conjunction with the establishment of the modeling and simulation environment in step 2 of the methodology. The project decomposition is described here in step 4 because it is more deeply interlinked with the game structure. At this point in the methodology, the design alternatives have been created for each project type.

The market scenario matrix established in step 1 (section 4.2.1) is revisited in step 4 by taking the previously specified scenarios and further expanding their attributes. Attribute values are indicative of a player's strengths and weaknesses in the ability to transform development projects into realized products for market sale. How fast a player transforms a project into product is the subject of the next section.

4.2.4.2 Project Uncertainty Modeling

In this research, two principle sources of uncertainty are assumed to be attributable to development projects. In conceptual design, engineers often have to assess the impacts of schedule uncertainty in their designs. This uncertainty corresponds to the likelihood of a design satisfying the customer requirements and meeting any budgetary constraints by a given date. The speed at which a design completes the conceptual design phase and begins production is based on those two conditions in addition to whatever uncertainties may be associated with integrating technologies.

There is however, a second source of uncertainty. Not knowing how competitors in the market are going to react to the introduction of a product refers to the competition uncertainty. In order to analyze the impact of this uncertainty on project selection, a game theoretic treatment is required. The game theoretic process is a way of analyzing a competitor's project strategies as a function of the project choices made by another competitor. This a unique way of finding a project solution that is potentially robust to uncertain market scenarios when there is often limited information about the competition. The selection of a robust project solution is the subject of step 5 in the methodology.

Schedule Uncertainty

The schedule uncertainty is modeled probabilistically by assuming independent log-normal distributions that describes the successful completion of a project. The probability that a project undertaken by firm i is completed by time t is:

$$Pr\left(\tau_{iN} \leq t\right) = \tfrac{1}{2} + \tfrac{1}{2} \times erf\left[\tfrac{\ln(T_{iN}) - \mu_{iN}}{\sigma_{iN}\sqrt{2}}\right] \qquad (for\ a\ new\ project) \tag{4.2}$$

and

$$Pr\left(\tau_{iD} \leq t\right) = \tfrac{1}{2} + \tfrac{1}{2} \times erf\left[\tfrac{\ln(T_{iD}) - \mu_{iD}}{\sigma_{iD}\sqrt{2}}\right] (for\ a\ derivative\ project) \tag{4.3}$$

where $\mu_{N(D)}$and $\sigma_{N(D)}$are the mean and standard deviation of either a new or derivative project completion time's natural logarithm. The parameter $T_{iN(iD)}$is firm i's mean completion time for a new or derivative project. This value is a function of two important assumptions commonly made in similar studies involving development project selection (Loury, 1979; Ali et al., 1993; Dasgupta and Maskin, 1987).

1. It is assumed that the expected time to develop a product from a *new* type of project would be greater than from a *derivative* type given a comparable allocation of resources to each project. This is consistent with the notion that a new development project typically has more inherent uncertainty in its development process compared to a derivative project where, for instance, the learning curve may not be as steep.

2. Secondly, firms will likely have differing approaches to developing and completing either a new or derivative project. This translates to a relative difference in the ratio of completion times for each project type. For example, one firm may have an advantage in transforming a derivative project into a final product compared to another firm. Therefore, their derivative project completion time will be lower than the derivative project completion time of the other firm. The completion times ratio between two firms follows the following relationship:

$$E_N = \frac{T_{1N}}{T_{2N}} \qquad and \qquad E_D = \frac{T_{1D}}{T_{2D}} \tag{4.4}$$

The enumeration of competitive scenarios in step 1 (section 4.2.1) is based on combinations of $E_N$and $E_D$values. The goal of performing the competitive analysis by varying the ratio of relative completion times is to represent instances where one firm has an advantage over the other in developing a project. Since it is difficult for firms to know exactly how fast they can produce a product compared to their competition, it is useful to analyze a spectrum of such competitive scenarios. Each scenario is then carried through the methodology and a payoff is computed for each firm based on the scenario. Eventually, by mapping all these scenarios with the project payoffs, the engineer will have a better understanding of which project is most strategically desirable to select.

Another important assumption is made in the choice of a log-normal distribution in representing the probability of a project being completed by a certain time. The log-normal distribution is the probability distribution of a random variable whose logarithm is normally distributed. These distributions are commonly used to model failure degradation processes like corrosion, diffusion, migration, crack growth, etc. and other reliability analyses. In large scale systems design projects, the development time-frame can also be characterized log-normally. The completion date of the development of a new aircraft for instance, will usually be set several years in advance. The probability that the aircraft is completed prior to that date is much smaller than the likelihood of it being postponed beyond that date. More often than not, large-scale systems design projects tend to overshoot their target date because of unexpected technical setbacks, market obstacles or budgetary issues.

Competition Uncertainty

The firms compete simultaneously in the market. A firm will select a development project with no knowledge of what project the other firm has decided to undertake. This uncertainty is addressed by listing all possible game scenarios and evaluating each through a structured game theoretic approach. When each firm has two choices available, the four possible game cases are shown in Figure 4.12. Each case represents a payoff value to each firm. If firm 1 undertakes a derivative project and firm 2 selects a new project, the payoffs are determined by computing case 3. Not knowing which project the competitor will undertake is the principal contributor of uncertainty in project selection. This follows a conventional approach by authors like Azevedo and Paxson (2007); Ali et al. (1993); Loury (1979), that evaluate competitive market uncertainty in similar investigations .

		Firm 2	
		New	Derivative
Firm 1	New	Case 1 [N,N]	Case 2 [N,D]
	Derivative	Case 3 [D,N]	Case 4 [D,D]

Figure 4.12: Four Competitive Game Scenarios

4.2.4.3 Game Payoff Calculations

Each game case shown in Figure 4.12 is a pair of payoff values, one for each firm. The payoff matrix is constructed in two parts. The first part involves calculating the market share for each game case and for each firm. This is done by evaluating the design alternatives with the customer criteria. The second part consists of determining all possible payoff scenarios that can arise from the game cases and the schedule uncertainty. The schedule uncertainty calculation described earlier in this step estimates how long it takes a firm to successfully complete a project given characteristic parameters, like average project completion times, etc. This information then helps determine which firm enters the market first and which one enters second. The market share matrix is then combined with these payoff scenarios to populate the payoff matrix. The execution of these two parts are described here.

Part 1: Populating the market share matrix

The design alternatives generated in step 2 of the methodology were grouped into the two types of projects, new and derivative. The assumptions made to distinguish a new project from a derivative project are problem specific. For this reason, those assumptions are described in detail for the engine selection problem in Chapter 5. In step 3, each design alternative from each project was mapped against the customer criteria (from each market segment) and ranked based on how well they performed against the criteria. This ranking is now used to calculate the market share for each design alternative from both firms. This

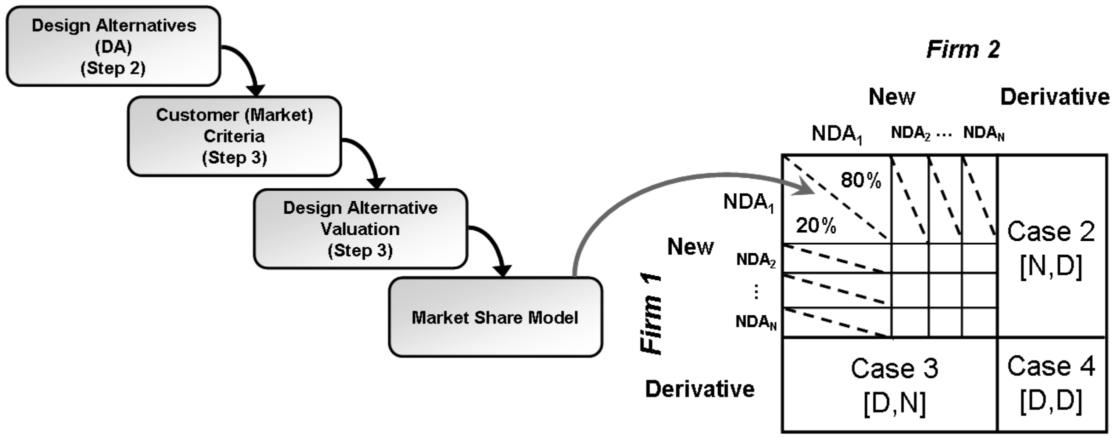

Figure 4.13: Market Share Matrix Development

process is shown in Figure 4.13.

Market demand determines which design alternatives are preferred by which customers. The market demand is modeled by having a pool of customers, each representing a different market segment. The customer criteria varies distinctly between market segments such that it is difficult for one design alternative to satisfy each market segment.

The market share model utilized in this research builds on the well-established attraction model by Bell et al. (1975). The design alternatives are evaluated based on the customer criteria defined by specific market segments. Each firm, i, has a design alternative, DA_{ij}, where j is the design alternative number. An *attraction value*, $a\,(DA_{ij})$ exists for each design alternative and is a function of the degree to which it meets the customer's criteria. An aircraft's attraction value for example, may be driven by its ability to meet fuel consumption demands, payload and range capabilities, emissions and noise regulations, etc. (The attraction value is computed in step 3 of the methodology). If $a\,(DA_{ij})$ is at or above the required level desired by a customer k, then it is assumed that the quantity of the product demanded by that customer, q_k, will be allocated to that design alternative. It can be stated then that

$$q_k\,(DA_{ij}) = f\,(a\,(DA_{ij})) \qquad for\ k = 1, 2, ..., n \tag{4.5}$$

An important assumption in this model states that the market share, $ms\,(DA_{ij})$, of a firm's design alternative, is uniquely determined by the quantity sold to a customer.

Therefore, this is formalized as

$$ms\left(DA_{ij}\right) = f\left(q_k\left(DA_{ij}\right)\right) \tag{4.6}$$

Furthermore, it can be said that

$$\sum_{i=1}^{n} ms\left(DA_{ij}\right) = 1 \tag{4.7}$$

where

$$0 \leq ms\left(DA_{ij}\right) \leq 1, \qquad i = 1, 2 \tag{4.8}$$

for a duopoly market. If a market share is assigned to each design alternative based exclusively on the quantity of design alternatives sold to each customer, then its market share is given by:

$$ms\left(DA_{ij}\right) = \frac{q_k\left(DA_{ij}\right)}{\sum_{k=1}^{n} q_k}, \qquad for\ k = 1, 2, ..., n \tag{4.9}$$

After computing a market share value for each firm's design alternative, the market share matrix is populated as shown in Figure 4.13. The market share matrix is then used to compute the payoff values to each firm when they select a design alternative. The payoff matrix will follow the project selection problem identified earlier in step 4 of the methodology. A full description of this project structure is presented in part 2.

Part 2: Populating the payoff matrix

There are four possible game cases that, when evaluated stochastically using the schedule uncertainty parameters, produce four market scenarios specifying which firm is the leader and which one is the follower. The leading firm is considered the market pioneer and is first to have successfully completed a project. The follower is the firm that introduces their product into the market at some point after the pioneer. The time frame where there exists only one product in the market is considered the monopoly period. When two products are simultaneously available in the market it is considered the duopoly period.

The payoff to a firm depends primarily on the following factors: the type of project they introduce into the market, whether they are a leader or a follower into that market and the rewards available in each period. A *first/second-mover advantage* parameter is used to study the advantages or disadvantages of being a leader in the market. This parameter also provides a means to understand the rivalrous relationship between firms and the impact that has on their payoffs. It is implemented in order to address RQ3.2 (Figure 4.2) which seeks to understand how the degree of rivalry between competitors affects project selection. This parameter is meant to encompass competitive factors such as price, which is driven by the number of players in a market and the degree of substitutability between their products. For example, in the duopoly period, firm 1 is the leader, firm 2 follows and each are in the market with differentiated products (one has new, the other derivative). If the products are highly substitutable then they may also induce price competition and so their payoffs are penalized accordingly. This penalty is modeled by through the first/second-mover advantage parameter. There is one parameter for products of similar type and one for differentiated products. Each will be explained later on.

The rewards available in each period are determined by the demands in the *new* product market and the *derivative* product market. These demands are only a function of the *value* of the product to the customers in the market. As described previously in Part 1 of this step, the values of a new and derivative product are computed in order to determine the market share between firms. The market share specifies the amount of rewards, $r_{iN}$and $r_{iD}$for a new and derivative product for firm i in each period. The rewards for the engine selection problem are the engine orders placed by the customers in the market. This will be discussed in detail in Chapter 5.

A firm receives monopolistic payoffs if its product is the only one available in the market. In the duopoly period, firms will receive payoffs depending on what products they have introduced into the market. All these possible market scenarios are enumerated in table 4.1.

In table 4.1, the total payoff to a firm is shown by adding the rewards attained in period 1 with those earned in period 2. For example, if firm 1 completes a *new* project before firm 2 completes a *new* project, the payoff to firm 1 is the addition of monopolistic rewards, r_{1N}, in the first period, with a fraction of the duopolistic rewards, $\alpha_{NL} r_{1N}$, in the second period, where $\alpha_{NL}$is the first/second-mover advantage parameter used to split the available rewards for a *new* project. The follower entering with a new project will have rewards decreased by

	Project Choice			Payoffs		
	Firm 1	Firm 2			Period 1	Period 2
Game Cases	N	N	Similar Products	Leader(N)	r_{iN}	$\alpha_{NL} r_{iN}$
				Follower(N)		$\alpha_{NF} r_{iN}$
	D	D	Similar Products	Leader(D)	r_{iD}	$\alpha_{DL} r_{iD}$
				Follower(D)		$\alpha_{DF} r_{iD}$
	N(D)	D(N)	Differentiated Projects	Leader(N)	r_{iN}	$\sigma_{NL} r_{iN}$
				Follower(D)		$\sigma_{DF} r_{iD}$

Table 4.1: Game Payoff Structure

α_{NF}equal to $1 - \alpha_{NL}$. Furthermore, the rewards for a new project will be higher than the rewards for a derivative project. For the engine selection problem, new engines will generally be priced higher than derivative engines which in turn will typically generate higher rewards for the manufacturer (either through direct sales or parts). This assumption is also echoed by similar analyses of consumer goods industries where pioneering firms will generally acquire a higher market share (Schmalensee, 1982; Robinson and Fornell, 1985). The use of separate first-mover advantage parameters, one for a new project and one for a derivative project, follows the assumption made by Ali et al. (1993) that a pioneering firm will have a relatively larger advantage in a market when introducing a new product versus a derivative product, i.e. $\alpha_{NL} > \alpha_{DL}$.

When both firms invest in different projects then the distribution of rewards is based on the type of projects chosen, the order of market entry, and the degree of substitutability between types of products. If for example, as shown in table 4.1, firm 1 is the leader with a new product and firm 2 follows with a derivative product, then the distribution of rewards in the duopoly period is based on the degree to which a new product will displace a derivative product. This *substitutability* parameter varies between 0 and 1 and is given by σ_{NL}, σ_{DF}, σ_{DL}, and σ_{NF}, depending on who is the leader/follower and what type of product they introduce into the market. The concept of substitutability is significant in the

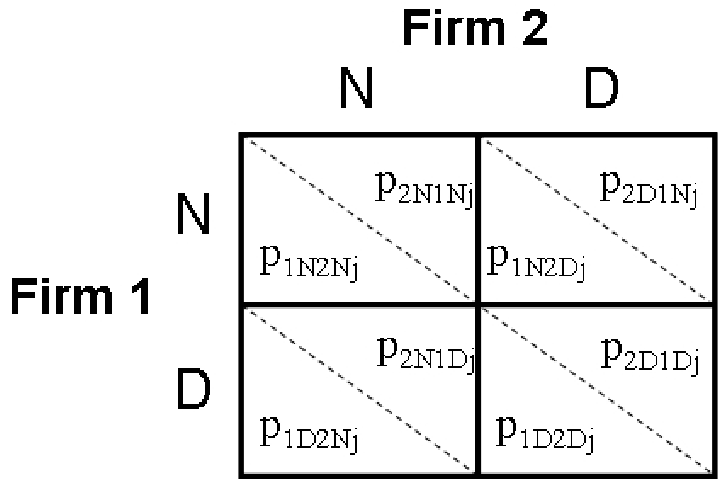

Figure 4.14: Expected Payoff Game Structure

development of aerospace systems and technologies. New and derivative aerospace systems differ mainly in the type of technologies used in those systems. Therefore, the degree to which a new or derivative product *displaces* the other will likely be driven primarily by the technologies infused within those systems. The value this parameter adopts can can be dictated by system performance metrics that are significant to the customer. The evaluation of this substitutability parameter will be made in Chapter 5 with the aircraft engine proof-of-concept.

The new and derivative project completion times, $\tau_{iN}$and $\tau_{iD}$for each firm i are evaluated stochastically via log-normal distributions following equations 4.2 and 4.3. These parameters are used to determine which firm is the leader and which is the follower for each game case scenario identified in table 4.1. The expected payoff calculations are made based on the model developed by Ali et al. (1993) which suggests that the expected payoff of a project to a firm is the combined discounted flow of rewards in periods 1 and 2. Figure 4.14 shows the payoff distribution structure to each firm when they select a design alternative from a new or derivative project.

The conditional expected payoff formulation to firm 1 entering the market first with a design alternative j from a new project given that firm 2 follows with a design alternative from a new project is given by:

$$p_{1N2N}\left(DA_j\right) = Pr\left(\tau_{1m} = t \,\&\, \tau_{2m} = s\right) \times \int_s^t r_N e^{-\mu u} du \,+\, \int_t^\infty \alpha_{NL} r_N e^{-\mu u} du \,-\, X_N \quad (4.10)$$

where:

- $Pr\left(\tau_{1m} = t \,\&\, \tau_{2m} = s\right)$ is the probability that firms 1 and 2 introduce their products at time t and s, respectively. The product type, m, is derived from a *new* or *derivative* project. Based on the assumption on schedule uncertainty (section 4.2.4.2), τ_1 and τ_2 are stochastic, so a firm may be a leader or a follower depending on the random date of the completion of the projects.

- $\int_s^t r_N e^{-\mu u} du$ is the flow of rewards, r_N, discounted by μ during the monopoly period.

- $\int_t^\infty \alpha_{NL} r_N e^{-\mu u} du$ is the flow of rewards, $\alpha_{NL} r_N$, discounted by μ during the duopoly period.

- X_N is the development cost for a *new* type of project.

This payoff formulation is a straightforward approach to calculating conditional expected payoffs given a time horizon. The methodology proposed in this research utilizes this approach as a foundation. In the selection of an engine architecture study in the next chapter, the discounted flow of rewards computation is carried out via a discounted cash flow analysis using appropriate financial models. In addition, the project development costs are integrated into the cash flow analysis.

The remaining seven payoff formulations illustrated in Figure 4.14 are devised in a similar fashion as equation 4.10. The payoffs are then compiled for each design alternative into a payoff matrix. This matrix is a type of game design space that enables managers to make a direct link between design alternatives and market opportunities.

The next step in the methodology is to explore the design space in such a way to choose an optimal strategy for project selection. Step 4 of the methodology is summarized in Figure 4.15.

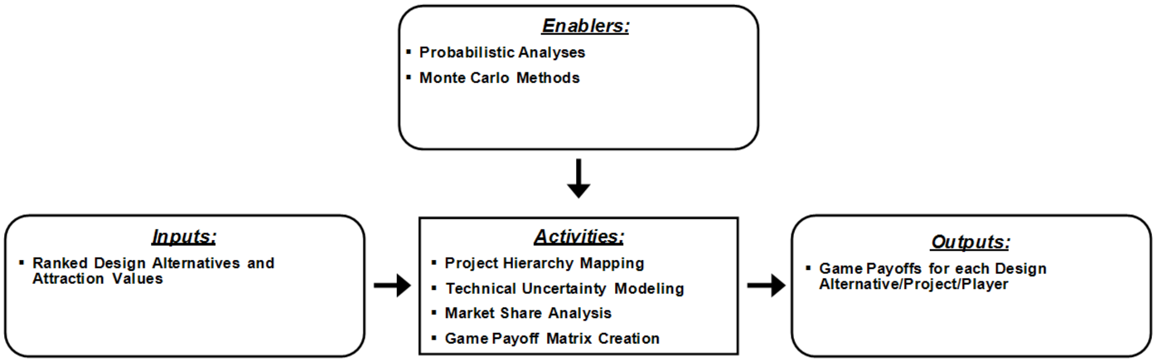

Figure 4.15: Step 4 Summary of Activities

4.2.5 Strategy Development and Decision-Making (Step 5)

The final step of the methodology begins by taking the game payoff matrix generated in step 4 and identifying the equilibrium solutions. These solutions represent robust choices of strategy in competitive scenarios with the purpose of mitigating potential payoff risk due to competitive market uncertainty. The equilibrium analysis uses concepts developed through the vast game theoretic literature. The second and final part of step 5 is where the project choice is made. The choice is primarily based on the equilibrium results. However, as will be discussed in Chapter 5, each project may have multiple design alternatives available, each with their own game equilibrium result.

4.2.5.1 Task 1: Identify Game Nash Equilibriums

Each payoff matrix is considered a game matrix for equilibrium[1] calculation purposes. As described in the literature review (Chapter 3) of game theoretic techniques, there are two types of game structures, normal and extensive form games. The normal-form structure is represented in the form of a matrix and differs from extensive-form games (game trees) in that information regarding the sequence of moves by players is not available. Normal-form games are easier to construct and evaluate which makes them more attractive when identifying dominated strategies and Nash equilibria. It is important to note that the framework proposed in this research lends it self to both normal and extensive-form game formulations.

[1]The equilibrium-finding method used in this research is based on the Nash equilibrium and therefore the word equilibrium here will be used interchangeably with Nash equilibrium.

However, the normal-form structure is the preferred approach to introduce the fundamental concepts of game theory and equilibrium analysis without the required additional information and computations needed for extensive games.

In this research, the author studies the competitive interaction between two players[2]. Evaluating this interaction is achieved by carrying out an equilibrium analysis using the techniques described in section 3.3. The selection of the best method for computing equilibria depends on several criteria. The methods applicable to a game depend on the number of equilibria to compute, the structure of the game (normal or extensive), and the rules of the game. The rules of the game as described in Chapter 3 dictate how the game is to be played. This information is critical to selecting the correct equilibrium solution-finding method. For this reason, the first step of the methodology, which formulates the project roadmap, is primarily concerned with explicitly outlining every element of the game to be analyzed.

A major driver in the selection of an equilibrium-finding method is the size of the game matrix. The larger the game (in terms of number of actions available to each player) the higher the probability of finding multiple equilibria. One of the major challenges with larger games (beyond 4x4) is attempting to choose a single equilibrium among the multiple solutions. By having a single point solution, game theorists would be able to predict what would happen during the game with more certainty. Furthermore, this would help players themselves in predicting what their opponents might do. Having multiple equilibria to choose from in a game may suggest that these are not genuine equilibria since each player may select a different equilibrium solution. This is a major hurdle to overcome in game theory and the literature proposes various modifications of the Nash equilibrium concept. Several attempts have been made to determine the "best" Nash equilibrium among a set of equilibria (van Damme, 2002).

In the proposed methodology the Nash equilibria are computed by solving systems of polynomial equations and inequalities. The method used to perform these computations is called "gambit-enumpoly" and is executed via the Gambit© software (See section 3.4). The input file specifies the type of game to be analyzed, the size of the matrix, and the payoffs

[2]For the purposes of this research, a firm is considered a player in the game.

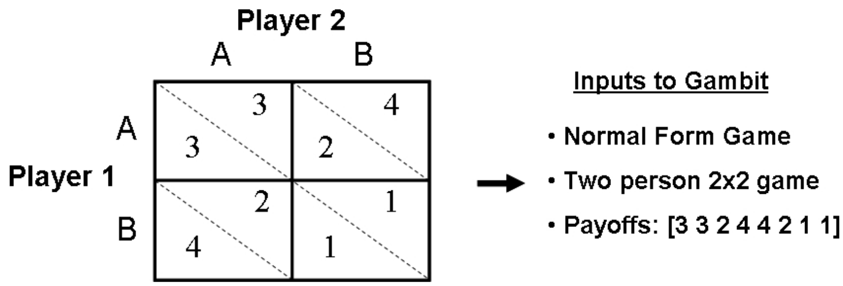

Figure 4.16: Example of Game Inputs into the Gambit Algorithm

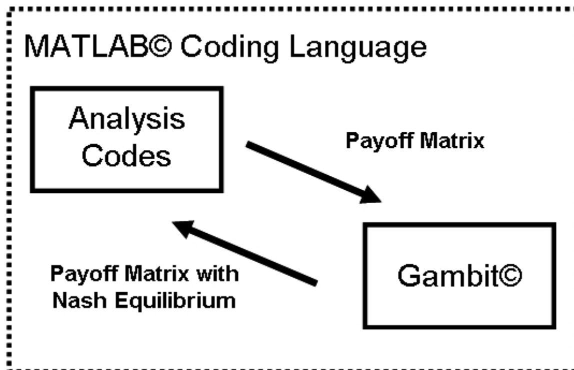

Figure 4.17: Linking the Analysis Codes with Gambit

for each player. An example of this input is shown in Figure 4.16.

The output file specifies the equilibrium strategy pair. If there exists mixed strategy equilibria the output specifies the probabilities of the mixed strategies. One of the major challenges encountered in this research was linking the game theory algorithm (Gambit) with the analysis codes used to generate the design alternatives. The state of the art in equilibrium analysis using computer algebra is currently limited to the Gambit software which provides an extensive toolkit for analyzing games but is limited to discrete experiment analysis. The output and input formats are not necessarily conducive to being automated which is a key criteria when running probabilistic analyses with varying payoffs. This problem is rectified by bypassing the graphical user interface of Gambit and directly "hard-coding" the gambit-enumpoly algorithm with the other analysis codes. The MATLAB© software is used as the platform to devise the experiment algorithms for this research (see Figure 4.17). Further details about the algorithm coding are provided in Chapter 5.

The project schedule uncertainty evaluation in step 4 (section 4.2.4.2) is essentially a sampling of input values from a probability distribution that change the payoffs of a game. Since this uncertainty analysis is performed over many samples the equilibrium analysis is therefore automated to perform the equilibrium computations for each payoff game. The equilibria are then compiled to observe how the schedule uncertainty affects the equilibrium outcome of competitive games. The next part of step 5 is where the decision-making takes places. The projects and their design alternatives are evaluated based on the equilibrium results (among others) and down-selected.

4.2.5.2 Task 2: Evaluate and Down-Select Project Strategies

The final part of step 5 re-introduces the research questions to observe how the proposed methodology addresses them as well as suggests other beneficial findings. In particular, Research Questions 3.1 and 3.2 are tasked with identifying the characteristics of a firm that influence project selection in competitive markets. The engine selection problem in this research is concerned with many types of decision criteria, ranging from technical metrics to economic and market metrics. As a result, the dimensionality of the problem increases rapidly and it becomes difficult for the decision-maker to make an engine selection. Fortunately, there exists a host of different down-selection techniques, like Pareto analysis, that facilitate the down-selection of designs. These techniques will be employed in Chapter 5.

It is not necessary to visualize every single output metric in order to make a decision. In fact, most of the time there will be conflicts between metrics making it impossible to identify a single optimal design. Ultimately, a compromise between metrics is required so that a design satisfactorily meets the most important requirements. One approach to facilitating the down-selection process is to evaluate each project and design alternative based on its "competitiveness" in the market. This can be defined in many ways but in this research the author has elected to define competitiveness in terms of expected payoff and risk (potential financial loss). The down-selection decisions then primarily focus on these two metrics. Both expected return and risk are based on the competitor's position in the market. For example, a new design project introduced into the market first can be financially rewarding initially during the monopoly period but may be less attractive once the competition enters with a

Rewards for Projects N&D (M$)		Investment Cost for Projects N&D (M$)		*New* Project Completion Time Range (yrs)				*Derivative* Project Completion Time Range (yrs)				Alphas for Leaders of a *New/Derivative* Project				Sigmas for Leaders of a *New/Derivative* Project			
R_N	R_D	X_N	X_D	T_{1N}		T_{2N}		T_{1D}		T_{2D}		α_{NL}		α_{DL}		σ_{NL}		σ_{DL}	
fixed	fixed	fixed	fixed	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9	6	5	2	1	4	1	4	1	4	1	4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 4.2: Base-case Model Inputs

derivative project. It is possible therefore, based on the project completion times for the projects from each competitor to determine their respective payoff and risk values. From a firm's perspective, the final selection of a design alternative is one which provides the most value to the firm, is robust to changes in customer demand, and its return on investment is sustainable across competitive scenarios.

4.2.6 Base-case Model

A base-case model is analyzed to provide insights into the sensitivities between the roadmap inputs (market scenarios, design alternatives, requirements) and the game theoretic tool outputs. The creation of a base-case model is essential to the overall research in order to calibrate the competitive analysis tools. This will alleviate the analysis of results in the proof-of-concept implementation in Chapter 5. The reader is referred to Figure 4.3 for an outline of the general assumptions made in the formulation of the base-case model. These assumptions will be reintroduced throughout the model setup.

The base-case model consists of two firms, each having two project options, that compete in a notional market where the rewards and development costs are fixed. This assumption shifts the focus from the impact of rewards/costs to the impact of the schedule (PCT) uncertainty. The market demand suggests that the potential rewards for a new product are higher than for a derivative product. Furthermore, the parameters for first and second (leader/follower) advantages are also fixed to a value of 0.5. This implies that during the duopoly period both firms receive 50% of the market rewards. This again helps to focus entirely on the impact of PCT fluctuations. The objective is to observe how the optimal project selection is driven by project completion times (PCT). The only independent variables in this case are the PCT's. The parameter settings are presented in table 4.2. The

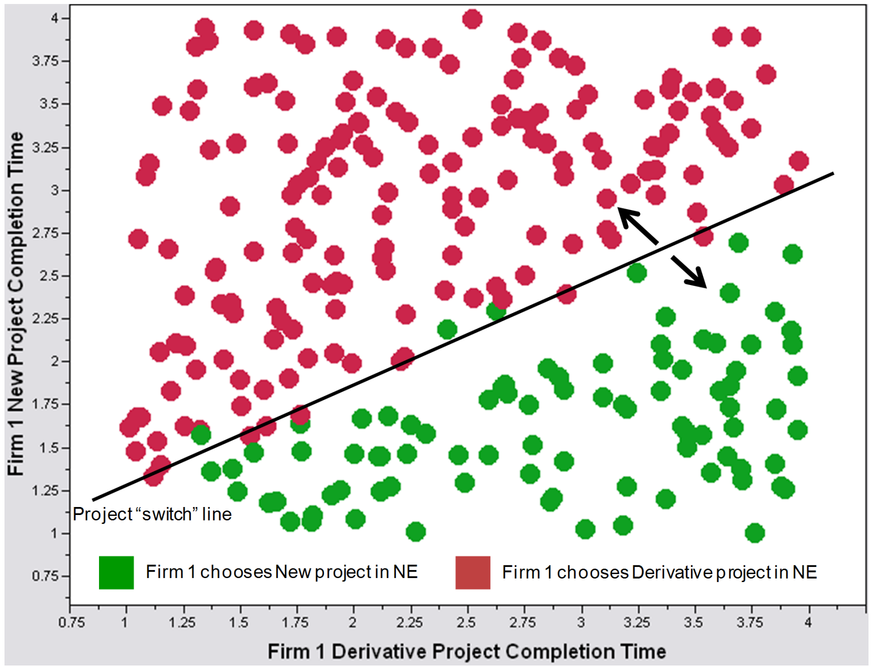

Figure 4.18: Market Scenarios for Firm 1's New and Derivative Project Completion Times

PCT's are vary uniformally between 1 and 4 years. A uniform distribution is assumed first to prevent the results from being skewed by the inputs. The base-case algorithm is run with 100 simulations for different PCT combinations to compute a payoff matrix for each market simulation. Each matrix is then analyzed to identify Nash equilibria using the Gambit game theoretic software as shown in Figure 4.17. The results are compiled to visualize how the NE results vary with different PCT scenarios. Figure 4.18 illustrates the market scenario results. The green and red points represent market scenarios where firm 1 should choose to develop a new and derivative project, respectively. The market scenarios are separated by a project "switch" line that suggests the PCT values where it would become optimal to switch project strategies. The Nash equilibrium shows that firm 1 would be inclined to convert a new project strategy to a derivative strategy if it estimates that the target PCT for new project is going to continue to increase beyond a threshold timeframe while its estimated PCT of a derivative project remains the same.

Another interesting result is to visualize how the payoffs for firms 1 and 2 change based on the project strategy choosen by firm 1. Figure 4.19 shows the payoff impact to firm 2 when firm 1 switches between a derivative and new project. Both firms seek to maximize

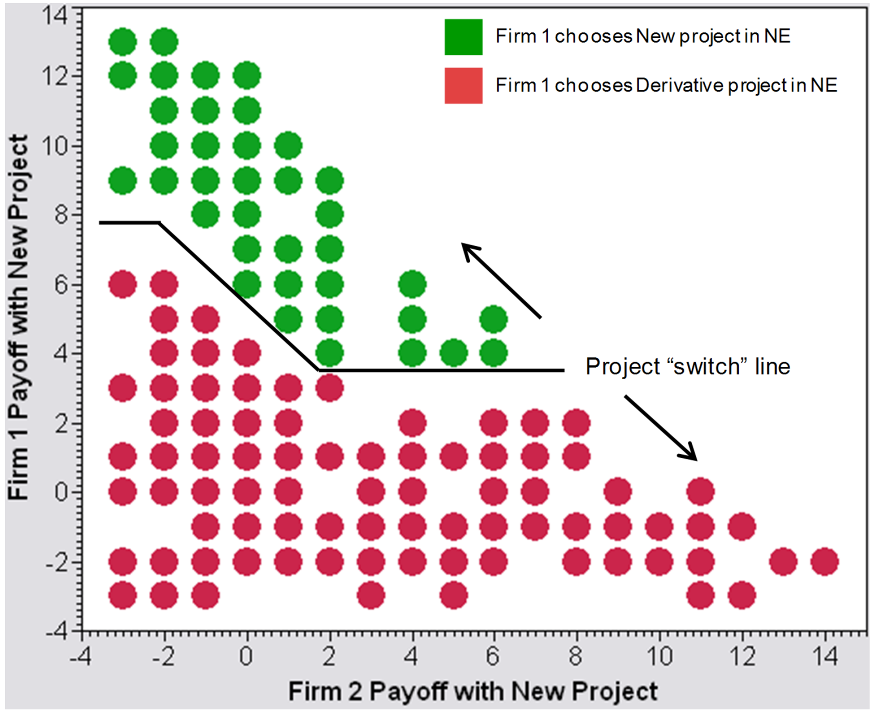

Figure 4.19: Market Payoff Scenarios for New Project Completion Times

their payoff for every game scenario. This "ideal" point would be positioned in the top right-hand corner of Figure 4.19. A Pareto frontier exists such that a payoff loss for firm 1 is a payoff gain for firm 2. The next base-case analysis consists of taking the same inputs from table 4.2 and changing the uniform distribution of the PCT's to a log-normal distribution. A log-normal distribution provides a more accurate representation of the probability that a project will be completed by a specified target date. The same base-case payoff algorithm is used and the Nash equilibria are calculated for 1000 market scenario simulations. The equilibrium results for a firm 1 and firm 2's PCT's are illustrated in Figure 4.20. The results depict four different equilibria that are possible for any combination of PCT's. From firm 1's perspective, an equilibrium scenario in either [N,N] (blue) or [N,D] (green) indicates that firm 1 should develop a *new* project. Similarly, an equilibrium result of either [D,N] (black) or [D,D] (red) suggests that firm 1 choose a *derivative* project to develop. The market scenarios plotted in this figure are a function of PCT's for new projects. The purpose here is to observe how the equilibrium trends as a function of uncertain new project completion dates. An important observation that emerges from these results is the "switch" year, where

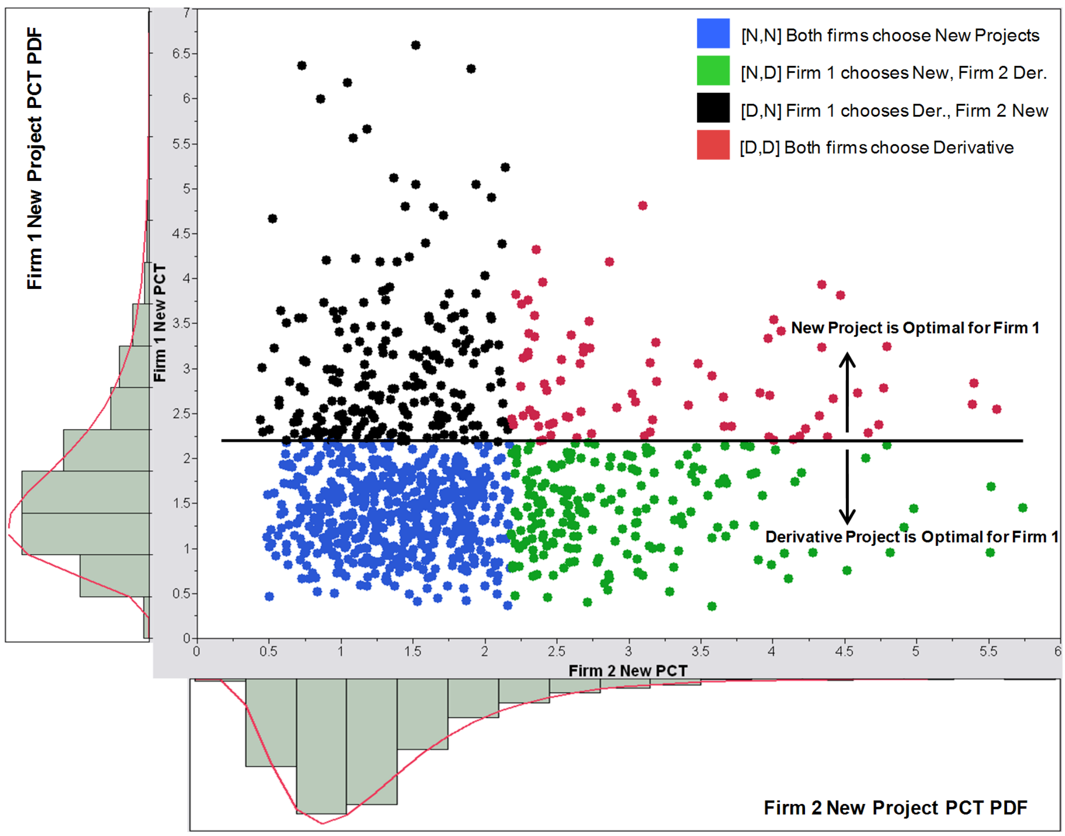

Figure 4.20: Market Payoff Scenarios for Log-normal Project Completion Times

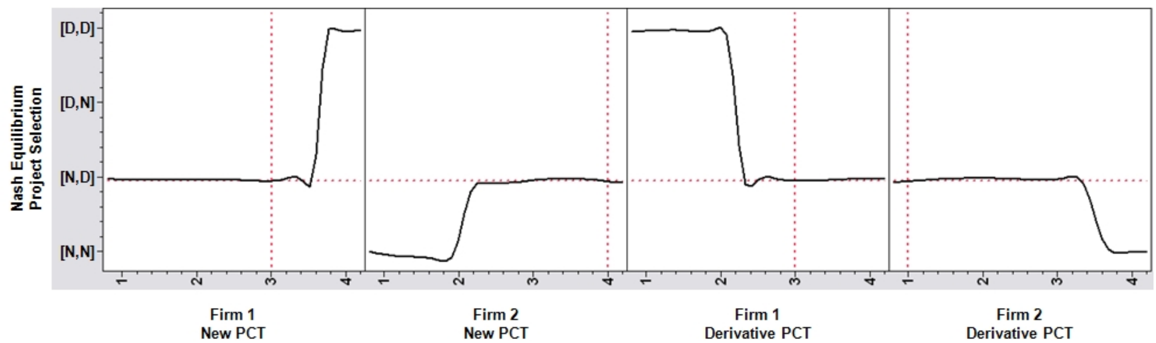

Figure 4.21: Base-case Equilibrium Surrogate Model Profiler

firm 1 would need to assess the likelihood that its new project development timeframe will go beyond ~2.25 years, in which case it should undertake a derivative project instead.

The next approach is to construct a surrogate model of the base-case payoff algorithm combined with the Nash equilibrium calculation. In addition to further equilibrium verification tests, surrogate models support decision-making on the fly. The equilibrium result can be attained by dynamically changing anyone of the input variables to any value within a specified range. This "game" design space is created through a design of experiments (DoE) with inputs listed in table 4.2. Each experiment in the DoE is run through the payoff algorithm and Nash computation. The model is created using the MATLAB© software. There are 1000 experiments in the DoE and each one constitutes a market payoff scenario. These scenarios consist of combinations of values of PCT's taken from a specified range, as shown in table 4.2. The surrogate model is constructed through the training of a Neural Network (NN) of 50 nodes. A NN is appropriate for highly non-linear functions, such as the Nash equilibrium space. A result showing one scenario of four PCT combinations is presented in Figure 4.21.

The surrogate model is used as a platform to verify the trends of the Nash equilibrium result. Figure 4.21 shows firm 1 entering the market first with a new product but follows firm 2 into the market with a derivative product. With these game settings the model suggests that the optimal choice of project for firm 1 is new and for firm 2 is derivative: [N,D]. These four PCT values are separately run through the payoff algorithm and Nash function and the resulting equilibrium is [N,D], which is indicates that the surrogate model is consistent with the algorithm and Nash calculations. This result is also intuitive since a firm will profit more by being a leader in the market so firms will tend to select projects which they believe they can introduce into the market before the competition. Surrogate models enable decision-makers to experiment with different project completion time settings and observe how the optimal project choice varies.

The main base-case takeaway is to demonstrate through a notional game example the ability to implement the payoff function and compute a payoff as a function of key R&D project inputs. It provided a platform to test the Nash function and observe the equilibrium trends. It also provided a basis for implementing and evaluating schedule uncertainty with different time-to-market scenarios. This model also begins to answer the second research questions which are presented here.

> **Research Question 2.1:** What competitive decision techniques enhance the confidence in concept down-selection of existing design methods in aerospace systems design?
>
> **Research Question 2.2:** How can decision-makers quantitatively measure the impact of a competitors product development strategy on the economic success of their design?

4.3 Chapter Summary

Chapter 4 introduced the methodology that is central to the development of the dissertation. At the beginning of the chapter, the research questions were posed and hypotheses were developed as means to guide the research process. Figure 4.22 illustrates the relationships between the methodology and the research framework.

The goal of formulating a specific methodology is to address each hypothesis by running the methodology through an experiment which will either prove or disprove each hypothesis. In the next chapter, the game-based methodology is implemented through an aircraft engine selection problem.

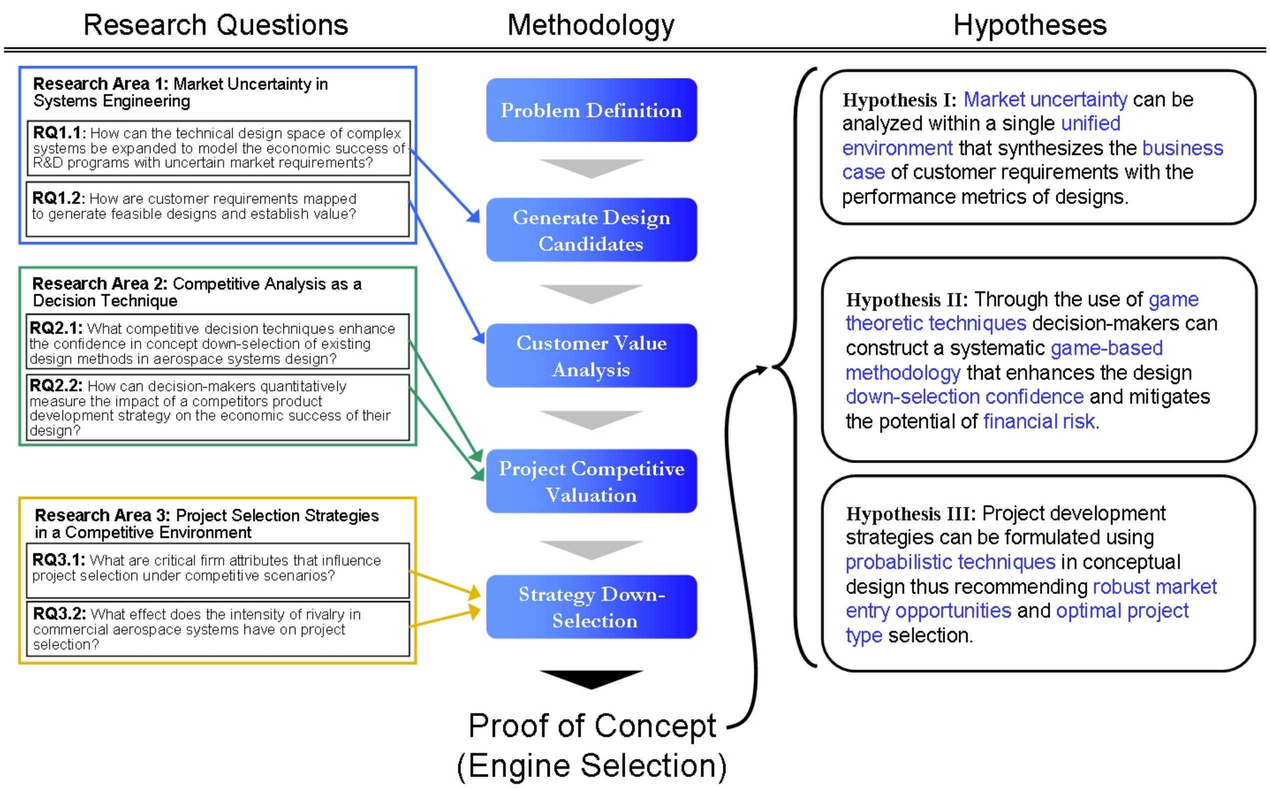

Figure 4.22: Recapitulation of Mapping between Methodology, Research Questions and Hypotheses

Chapter V

CASE STUDY: SELECTION OF A COMMERCIAL ENGINE ARCHITECTURE

The selection of a commercial engine architecture is the demonstration problem for the proposed methodology outlined in Chapter 4. The intent in this chapter is primarily to show that the method can be completed and applied to a current engineering problem. The demonstration problem also serves as a testbed for answering the research questions and evaluating the hypotheses established in section 4.1. It is important to keep in mind that the results presented throughout this chapter are hypothetical, based on a series of important assumptions that will be introduced where necessary.

The structure of the chapter is based on the steps of the methodology. The first section begins with an introduction into the commercial engine selection problem. A significant amount of effort is devoted to steps 2 and 3 which detail how the engine design alternatives are generated and evaluated in terms of their technical and economic performance. At the outset of this doctoral research, the focus was primarily on the development of a commercial engine design environment where decision-makers could evaluate different engine alternatives under various economic conditions. A broad modeling and simulation environment was developed for this purpose. As the research progressed into the competitive market arena this environment grew concurrently to assess the competitive effects of different market scenarios.

5.1 Problem Introduction

Section 1.5 introduced some examples of competition in the aerospace market. The proposed methodology is applied to the engine architecture selection problem of a 300 passenger commercial jetliner with market competition.

The problem is inspired by Boeing's development of the Boeing-777 in the late 1980s and

Figure 5.1: Boeing 777LR with GE90-110 Engines (Boeing Commercial Airplanes, 2008)

early 1990s[1]. However, the engine selection problem in this research is not meant to exactly imitate that design problem. The real B777 engine selection problem serves as a guidance throughout the implementation. In particular, throughout the development of the M&S environment and the creation of the engine design space, an attempt is made to conform to the technical specifications of the B777 engines.

The B777 market was chosen as the proof-of-concept for this research for several reasons. There is more flexibility from a sizing and synthesis standpoint when considering large turbofan engines. The B777 aircraft was (and still is) outfitted with the largest commercial turbofan in the world (Figure 5.1) . The engine analysis codes used in this research are capable of generating a wider range of engine alternatives that can satisfy the performance requirements of the B777 than if they were to generate alternative designs for smaller aircraft categories. The competition between the three B777 engine manufacturers, General Electric, Rolls-Royce and Pratt & Whitney demonstrates how three different engine manufacturers with varying engine architectures can compete on an airframe. Only very few airframes exist in the market, like the B747 and B767, that are offered with a choice of engine from

[1]See section 2.1.1 for background on the B777 engine selection problem.

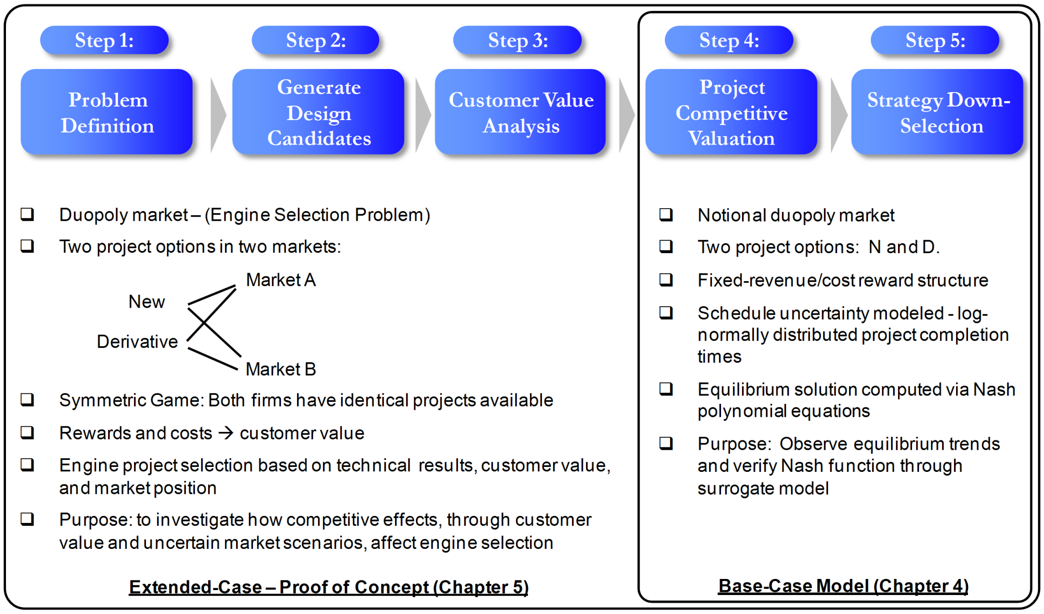

Figure 5.2: Five-Step Methodology for Analysis of Competitive Designs

all three major engine manufacturers. Much of the decision to use the B777 as a case study was dependent on the modeling and simulation capabilities of the technical framework in this research. More on the modeling of B777 engines is presented in step 2 in this chapter.

An illustration of the methodology is reintroduced in Figure 5.2 to remind the reader of the sequence of steps for the implementation process.

5.2 *Step 1: Project Selection Problem Definition*

The first step of the methodology can be regarded as the backbone of the implementation process. The problem definition step determines the structure and direction the experiments will take. It begins with Quality Function Deployment to identify the key requirements and engineering characteristics. A matrix of alternatives then utilizes the QFD information to develop project alternatives for the engine manufacturers.

5.2.1 Quality Function Deployment

The problem definition step starts by confirming the already established business case of the design problem. In the case of the engine selection, this would consist of gathering all the pertinent information from the different business units within the firm, like marketing, engineering, etc. and consolidating this information to develop the best strategy. The approach in step one of this methodology is to simulate the formulation of a business case through a Quality Function Deployment (QFD) and analysis of alternatives. One of the main advantages of a QFD analysis is to provide a planning route from the top-level product requirements, through the part characteristics, through the process parameters, to the component level and how everything will be manufactured. In this experiment, a QFD is performed for a 300 pax aircraft (product) but focusing only on the engine characteristics. It is important to note that the QFD would integrate all the suppliers to the airframe (like the engine) together to plan a successful development approach. However, the assumption in this experiment is that a QFD for the airframe has already been carried out.

The QFD is performed to translate the customer requirements of a notional 300 passenger aircraft to the engineering characteristics of an engine manufacturer for that airframe. The first step in the QFD analysis is to populate the customer requirements rows. The analysis requires that these attributes be expressed as measurable design targets in the form of engineering parameters. The "voice of the customer" can be categorized into four main areas: performance requirements, regulatory requirements, operations and safety, and economics. Figure 5.3 shows the house of quality for the proof-of-concept. Each category is divided further to include specific design attributes such as range, number of passengers, risk, noise production, emissions, maintainability, direct operating cost, etc. Each attribute is given an importance value by the customer. These will help compute the relative and weighted importance of the engineering characteristics later on.

The next step involves populating the engineering characteristics. These are design parameters that the engineer has control over to address each customer attribute. For this aircraft study there are categories like: performance, structures, costs, and propulsion. Each has specific characteristics like: sea level thrust, engine weight, number of spools, SFC, takeoff field length, Mach number, material selection, etc. In most design problems the engineering characteristics are correlated with each other. This information is inserted into the correlation matrix (roof of the house of quality). This involves looking at the coupling between characteristics and specifying a degree of correlation. For example, the

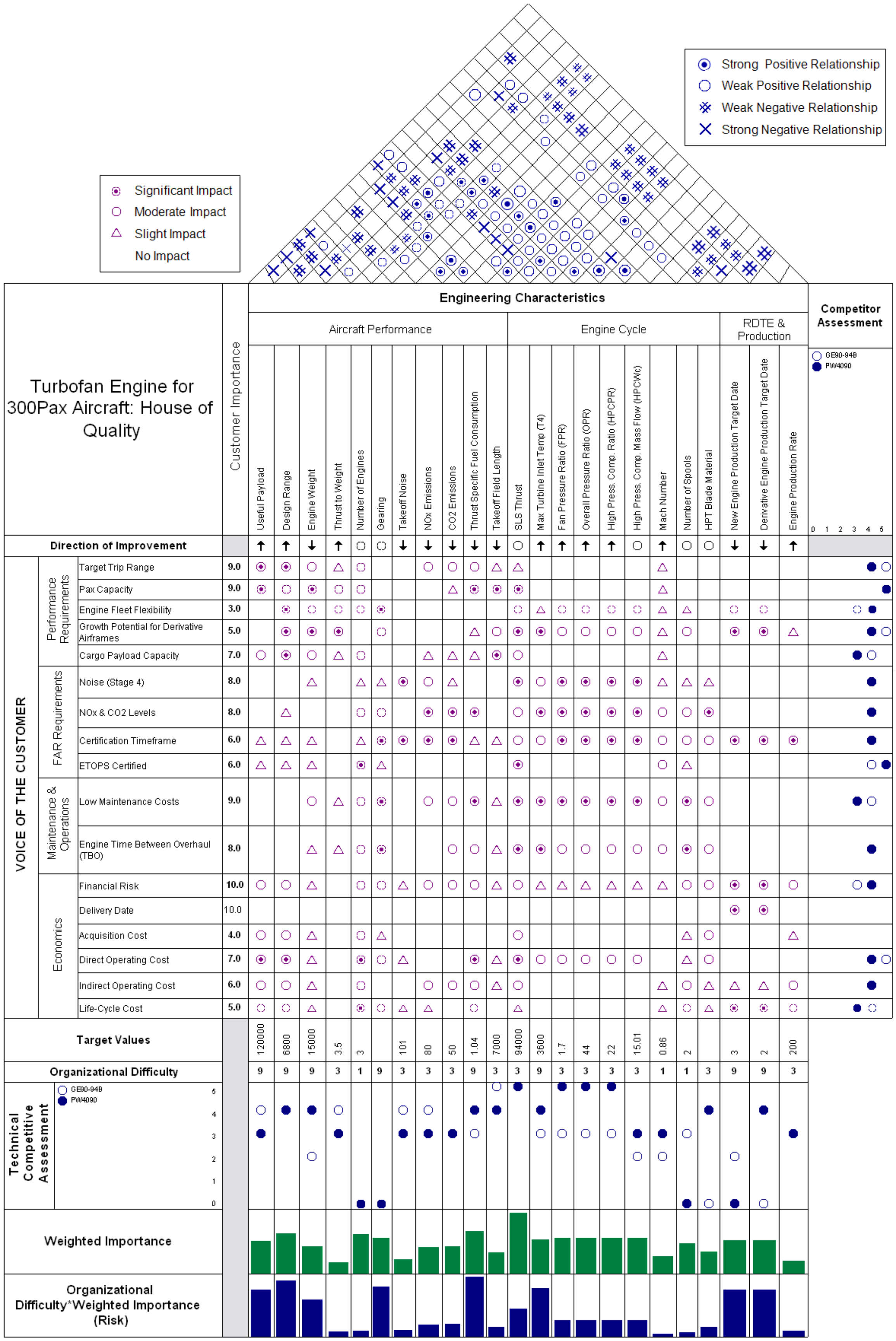

Figure 5.3: Engine House of Quality for 300 Pax Aircraft

engine weight is strongly correlated with the number of compressor stages. This assessment may indicate that a further trade study is necessary between these characteristics.

Once this information is added to the house of quality, the relationship matrix is then populated. The relationship matrix will determine the degree to which the engineering characteristics impact the customer needs. For example, the engine weight strongly impacts the passenger payload of the aircraft. The scale of the correlation is generally nonlinear of the form 9/3/1/0.

For each engineering characteristic there are specific target values which are listed at the bottom of the house of quality. The organizational difficulty nonlinear scale provides a way of identifying which engineering characteristic targets will be most difficult to achieve.

A technical competitive assessment is made which benchmarks the firm's engine against other competitors engines for each of the engineering characteristics on a scale of 1 to 5 (best). In the QFD analysis the competitive assessment is important as it is the the first take on at addressing what the competitor is producing.

The weighted importance of each engineering characteristic is computed based on the importance rating of each customer requirement. The scale of organizational difficulty is way of showing how difficult it will be to achieve the target values under schedule uncertainty. A nonlinear (9/3/1) difficulty scale is appropriate to separate those metrics that are higher risk from those a lower risk. This scale will then impact the distribution of the relative importance. The relative importance is the weighted importance, normalize on a scale from 1 to 100. The results of the QFD are used to populate the matrices of alternatives. This distribution shows that sea-level static thrust, TSFC, design range, and several other metrics have the most impact on the customer requirements. This study confirms that engine design candidates must be created with these metrics in mind. Furthermore, the cycle parameters, Fan Pressure Ratio (FPR), Overall Pressure Ratio (OPR), Turbine Inlet Temperature (T4), High Pressure Compressor Ratio (HPCPR), and High Pressure Compressor Weighted Inlet Mass Flow Rate (HPCWc) have a direct impact on Thrust Specific Fuel Consumption (TSFC).

The final step is to calculate the product of the weighted importance and the organizational difficulty to identify the relative weighting of engineering metrics with the highest organizational difficulty. This is represented by the bar chart at the bottom of the House of Quality. This result is added value in determining the difficulty of achieving the engineering targets. This bar chart represents the risk embedded in each engineering characteristic. The risk is driven by factors such as low technological knowledge with respect to achieving the engineering target, or by the schedule and costs associated with meeting those targets. Although some engineering metrics like SLS thrust have an important impact with respect to the customer requirements, the risk results indicate that TSFC is going to be a more significant metric to consider, based on the difficulty associated with achieving its target.

The next step involves constructing the engine and customer matrices where the QFD results will help identify which parameter values to select.

5.2.2 Matrix of Alternatives

Performing a QFD analysis first, before populating the matrices is beneficial because it determines which customer requirements are more important and it helps to formulate alternatives based on the results of the engineering characteristic impacts. The QFD's relative importance analysis also serves as a guide to select the optimal choice of scenarios from the matrices. There are four matrices that are necessary to bound the scope of the proof-of-concept.

The first step is to do a functional decomposition of the engine based on the engineering characteristics from the QFD. The matrix attributes in the rows are the engineering characteristics in the QFD. The project alternatives are established based on a review of existing engine designs from competing manufacturers as well as technological advances that exist in industry. This matrix is illustrated in Table 5.1. The highlighted cells indicate a chosen alternative for a specific engine attribute. The row is the called "presets". These represent notional engine alternatives and when selected are made up various combinations of attributes. The bottom five attributes are engine cycle parameters that determine the

Table 5.1: Project Matrix of Alternatives

		Alternatives				
Engine Functional Decomposition	Presets	New Arch. 85k Thrust	New Arch. 94k Thrust	Der. Arch. 77k Thrust	Der. Arch. 90k Thrust	
	Engine Type	Mixed Flow Turbofan	Separate Flow Turbofan	Combined Cycle		
	Gearing	Geared	Not Geared			
	Number of Spools	1	2	3	Contra-Rotating	
	Compressor	Booster Stage	No Booster Stage			
	Nozzle Type	Converging	Converging-Diverging	Variable		
	Turbine	1 Stage HPT	2 Stage HPT			
	High-Temp Material	Titanium	Nickel-alloy	Carbon Composites	Metal Composites	Ceramic Composites
	Cooling Scheme	Convection	Impingement	Film	Transpiration	Liquid
	Noise Reduction	High Bypass Ratio	Scarf inlet	Chevron Nozzles	Active Noise Control	Forward Swept Fans
	New/Derivative Engine	New	Derivative			
	Target Customers	Single Customer	4 Primary Customers	50% Market	100% Market	
	OPR	36	3	44	3	
	FPR	1.48	1.56	1.6	1.7	
	HPCPR	11	3	20	3	
	HPCWc	14.6	15			
	T4_takeoff	3300	3400	3600	3800	

Table 5.2: Customer Requirements Matrix of Alternatives

		Alternatives				
Customer Requirements	Preset Airline Customers	Airline 1	Airline 2	Airline 3	Airline 4	Airline 5
	Base A/C Utilization Type	Short-Range Med LF	Short-Range High LF	Med-Range Med LF	Med-Range High LF	
	ER A/C Utilization Type	Med-Range Med LF	Med-Range High LF	Long-Range Med LF	Long-Range High LF	
	A/C TOFL Requirement	<9000	<10000	<11000	<12000	<13000
	Expected No. of A/C Orders	20	3	60	3	
	A/C Utilization/day (hours)	8	12	14	18	
	Average $/RPM	0.1	0.12	0.15	0.17	
	Delivery Year (from today)	2 years	4 years	6 years	8 years	

cycle of an engine design alternative. In the next step of the methodology a design of experiments is constructed around these cycle parameters to generate feasible engine candidates. The values of these parameters are presented here deterministically. In the design of experiments, however, they will be allowed to vary based on a range determined from the values highlighted in this matrix of alternatives.

The next matrix relates to the customer requirements. The QFD information is directly implemented here again to populate the attributes on the left-hand side of the matrix in Table 5.2. For the proof-of-concept, two markets are used to evaluate the engine designs from each firm. The first market (A), represents a base range aircraft that would carry a specific payload for a base design range. The second market (B), is an extended range derivative of the first airframe. The customers in this proof-of-concept consist of different airlines, with different preferences and fleet routes, that are going to commit to buy an aircraft (either A or B) with a choice of engine from two available engine firms in order to

Table 5.3: Game Structure Matrix of Alternatives

		Alternatives		
Game Structure Attributes	Number of Players	Single (Decision Theory)	Two	N-players
	Available Actions (Type of Project)	Single	Sequence of Projects	Portfolio of Projects
	Information Set	Perfect Information	Incomplete Information	
	Number of Game Stages	One-Stage	Two-Stage	Multi-Stage
	Order of Play (Timing of Investments)	Sequential	Simultaneous	
	Analysis of Equilibria	Pure Strategies	Mixed Strategies	

maximize their utility. The utility of an airline in this research is determined by the net present value (NPV) of their investment in an aircraft/engine package. This utility analysis is the subject of step 3 in the methodology. The matrix of alternatives for the customer requirements consists of five predefined airline *profiles*. Five airline profiles is assumed to provide a good distribution of differences between airlines currently operating worldwide. Each profile specifies the preference of that airline with respect to the list of attributes listed in the rows of Table 5.2. The customer value analysis (step 3) can be performed with either one airline representing the entire market or 'n' airlines. The approach taken for this proof-of-concept experiment is to use the five airlines as representations of different market segments in the global aviation marketplace. It's important to note however, that the very first experiment consisted of only one representative airline. The goal initially was to focus less on what the market demanded on more on what the firms had to offer. As the research progressed, more airline profiles were added to provide a healthier representation of the market diversity. For an engine manufacturer, it is more rewarding to capture more than one segment of the market with the same product.

At this point the focus shifts from the project alternatives and customer requirements definition to defining the experimentation process of the methodology. The next matrix of alternatives illustrates the various game structure possibilities that exist when analyzing competition between players. Table 5.3 shows the different alternatives that are possible for a variety of game attributes. The reader is referred to section 4.2.1.1 for a more detailed description regarding the choices made for this particular game structure. Of interest in

Table 5.4: Market Scenario Matrix of Alternatives

		Alternatives			
Market Scenario Attributes	Preset Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Mean PCT Firm 1 NEW	4	6	8	10
	Mean PCT Firm 1 DER	0.5	0.75	1	1.5
	Mean PCT Firm 2 NEW	1	2	5	7
	Mean PCT Firm 2 DER	0.5	0.75	1	1.5
	Sigma_New	0.2	0.3	0.4	0.5
	Sigma_Der	0.05	0.1	0.2	0.5
	Alpha_NL	0.3	0.4	0.7	
	Alpha_DL	0.8	0.9		
	Sigma_NL	0.1	0.5	0.8	0.9
	Sigma_DL	0.3	0.4	0.5	

this research is the competition in innovation investment. As engineers we want see what effect does time-to-market have on our selection of designs. Smit and Trigeorgis (2004) provide a framework for simultaneous and sequential games under various scenarios of R&D investment competition. These scenarios are used to help formulate the game framework for this proof-of-concept. Again, the focus is on simultaneous investment decisions made by firms that feel the competitive pressure to rush into an innovation.

The last matrix of alternatives describes the options available to study the different market-entry timing scenarios. Table 5.4 shows the options available to describe a market scenario. The information contained in a market scenario is specifies the range of a firm's project completion time frame. With this information it is possible to identify a leader and follower in the market. The mean PCT's for each firm and their respective projects are used to build the log-normal distributions that represent the uncertainty in project development duration. The sigmas for each project determine the spread of the log-normal distribution from the mean target PCT. The alphas and sigmas for each project leader specifies how the rewards are distributed in the monopoly and duopoly periods.

The results of step 1 establish the roadmap that the proof-of-concept will take. As shown in Figure 4.6 of Chapter 4 the objective of this first step is to provide the groundwork for the subsequent steps in the methodology. Since each step builds on the next it is crucial to specify the structure of the entire methodology prior to generating results.

5.3 Step 2: Generate Design Candidates

With a clear definition of the types of projects and design alternatives that are going to be evaluated for competition, the focus shifts to generating these engine designs. The top-down/bottom-up approach that was illustrated in Figure 4.8 (Chapter 4) determines the mapping of the customer requirements and market segments to the engine design alternatives. There are five airlines profiles that are set up to represent five different market segments for the 300 passenger aircraft market. The segmentation of the market is made based on existing routes by airlines using the B777-200 and B777-200ER airframes. The primary goal is to provide a distribution of airline profiles that captures a wide range of operating characteristics. The airlines profiles are notional but were loosely based on operating characteristics of existing airlines. At this point, the only information necessary to generate the design alternatives are the main customer value metrics that determine what engine outputs to track.

Each of the five airlines has different requirements in terms of aircraft utilization, takeoff field length, expected engine orders, delivery dates, etc. These are value metrics that take on different values based on the preferences of the airline. Although there are many more metrics that are necessary to differentiate airline customers, these were selected from the problem definition in step 1 as the those that would have the largest impact on the utility of the airline. These metrics were also selected to help distinguish the impact of each engine alternative from each other. It's important to note that the design of an aircraft engine has an important but limited impact (mainly through the performance of the aircraft and maintenance) on the airlines' utility whereas other financial and operations metrics are more common when looking at airline requirements. However, the purpose of this research is to identify how the engine design can directly impact the utility of an airline. A full description of the airline profiles is provided and discussed in the customer value analysis in step 3. The focus here to generate the engine design space.

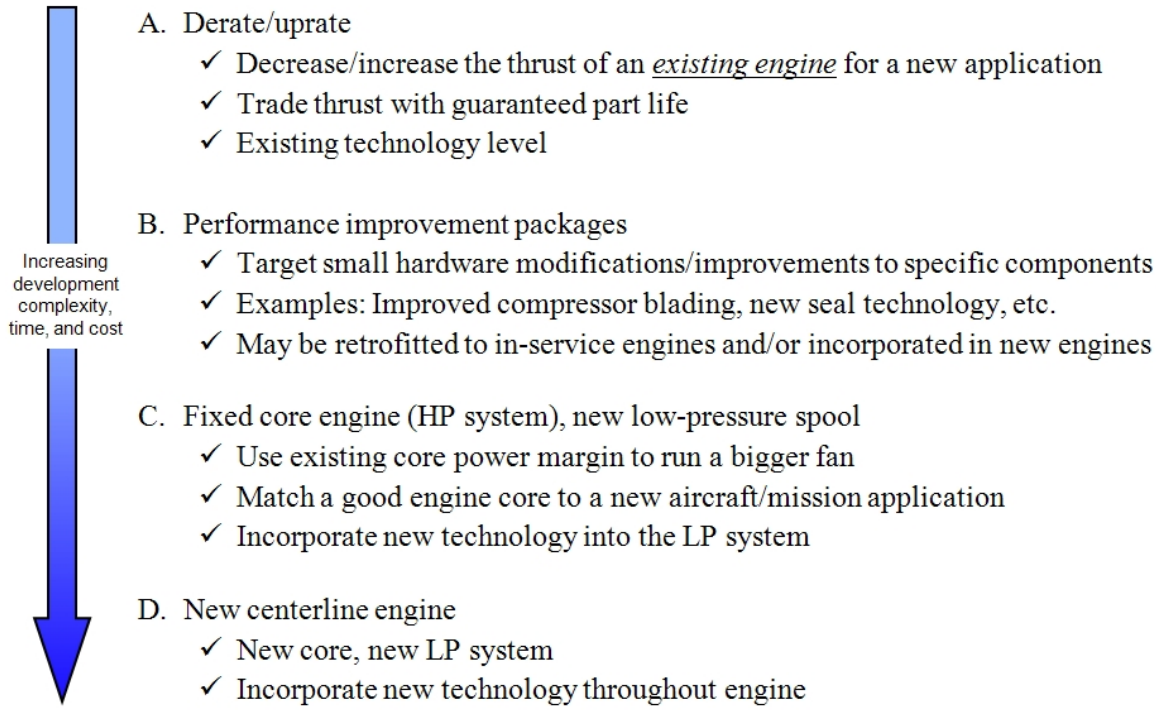

Figure 5.4: Engine Architecture Decision Path

5.3.1 Engine Design Space

The proof-of-concept studies two types of projects, *new* and *derivative*. The definition of a research and development project in this study is based on how engineers define the difference between a new and derivative engine architecture. Defining the basic architecture of an engine is the first step that needs to be made. This stems from the fact that the architecture is earliest decision and the most difficult to revisit in the future. To understand the spectrum of options available, a flowchart of engine architectural decisions is illustrated in Figure 5.4.

In this research, option C is considered a *derivative* project and option D a *new* project. To guide the engine parametric environment these two different architectures were chosen based on existing engines and their flow-paths are illustrated in Figure 5.5. Once the two engine projects are chosen the next part of step 2 is to produce a large set of engine designs for each project by means of varying design cycle parameters. A DoE is created for each

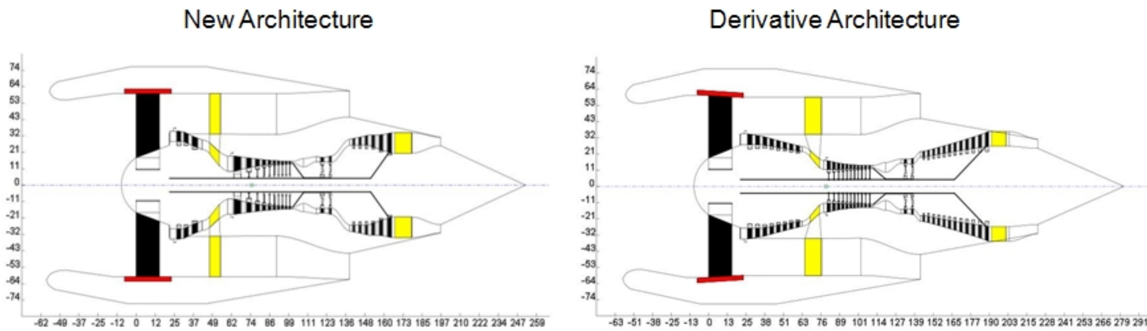

Figure 5.5: Engine Flow-paths For a New and Derivative Architecture

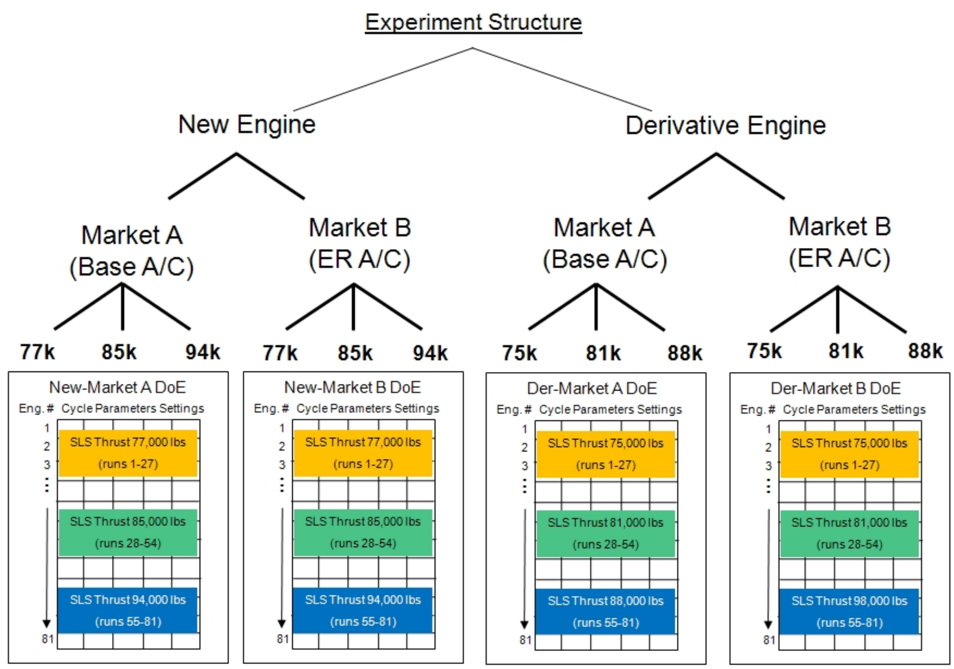

Figure 5.6: Engine Design of Experiments Structure

engine project and for both markets (base range and extended range aircraft) as shown in Figure 5.6.

Five cycle parameters were selected as design variables for the DoE. These are shown in table 5.5. A central composite design (CCD) was generated using these design variables and a total number of runs was 81 for each of the four DoE's. The DOE is then run through the Environmental Design Space (EDS) modeling and simulation environment which contains a suite of analysis modules/tools that represent the different aspects of engine design and aircraft mission analysis. Each module consists of an analysis method which is either

	New Architecture		Derivative Architecture	
Design Variable	Min	Max	Min	Max
Overall Pressure Ratio	41	45	38	44
Fan Pressure Ratio	1.48	1.56	1.6	1.7
High Pressure Compressor Pressure Ratio	20	22	11	13
High Pressure Compressor Inlet Mass Flow (Normalized)	14.6	15	14.61	15.01
Maximum T4 (°R)	3400	3600	3400	3700

Table 5.5: Design Variable Ranges for DoE

a physics-based analysis code or analysis method with an empirical database. The EDS platform in Figure 5.7, was commissioned by the FAA office of environment and energy for the purpose of having a simulation capability for investigating the interdependencies and trade-offs associated with environmental policies and technology development goals (Georgia Tech and MIT - PARTNER, 2007). The detailed modules comprising the EDS tool were originally developed by the National Aeronautics and Space Administration (NASA) and include five modules which have been seamlessly integrated:

- Numerical Propulsion System Simulation (NPSS) – calculates the engine thermodynamic analysis
- Weight Analysis of Turbine Engines (WATE) – estimates component weights and dimensions based on cycle parameters calculated in NPSS
- FLight OPtimization System (FLOPS) – calculates aircraft weights and performance results based on mechanical model from WATE and cycle performance from NPSS
- Aircraft Noise Prediction Program (ANOPP) – predicts certification noise levels and noise power distance curves, based on aircraft dimensions from FLOPS and engine information from NPSS and WATE

The NPSS cycle analysis performs a multi-point design at sea-level static, takeoff, top-of-climb, and an aero-design point (cruise). This cycle analysis is more accurate than designing

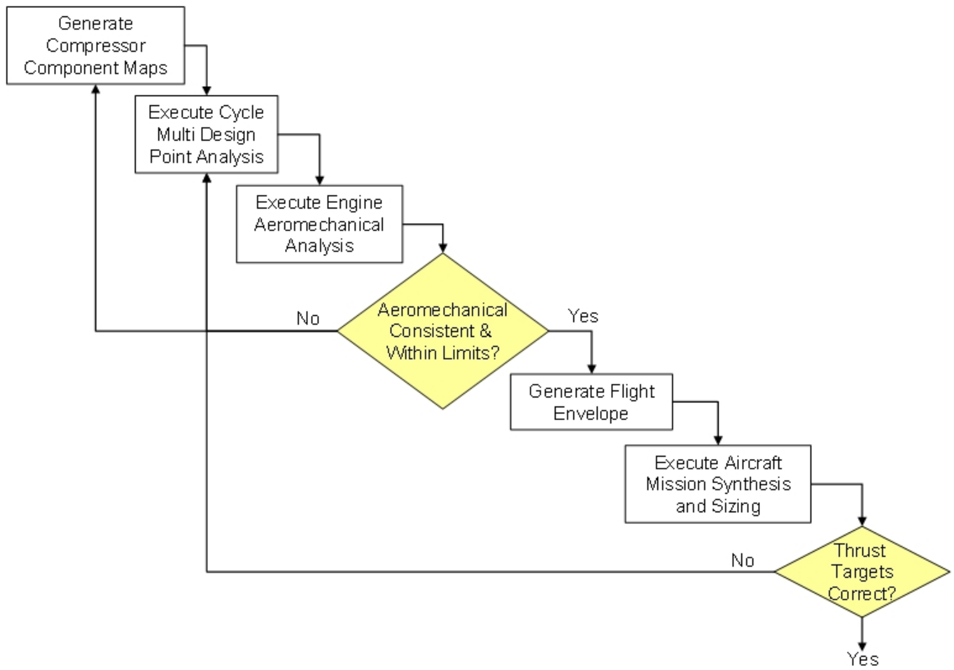

Figure 5.7: Engine Environmental Design Space Environment (Georgia Tech and MIT - PARTNER, 2007)

the engine for a single point in the mission. Off-design analysis points that span the mission are also included. The analysis code generates various outputs from the cycle analysis including TSFC and thrusts at takeoff and top-of-climb (SLS thrust is an input). The WATE analysis code generates the weight outputs for each engine design. These include all the weights for all the components of the engine. The total engine weight is important when it comes to sizing the airframe for the mission. It will also be key in determining the amount of aircraft payload available. The FLOPS analysis is perhaps the most important in terms of mission potential as it computes the fuel burn for each engine based on a specified mission input. It also estimates the Takeoff Field Length (TOFL) required for each engine. The estimated TOFL of a sized aircraft/engine combination is typically a design constraint in design. Since the runway length is fixed by the design of the airport designers must incorporate this constraint into their sizing analysis. This metric may be more important to some airlines than others based on the runways they operate from. The engine results from the four experiments are compiled together and presented in Figure 5.8.

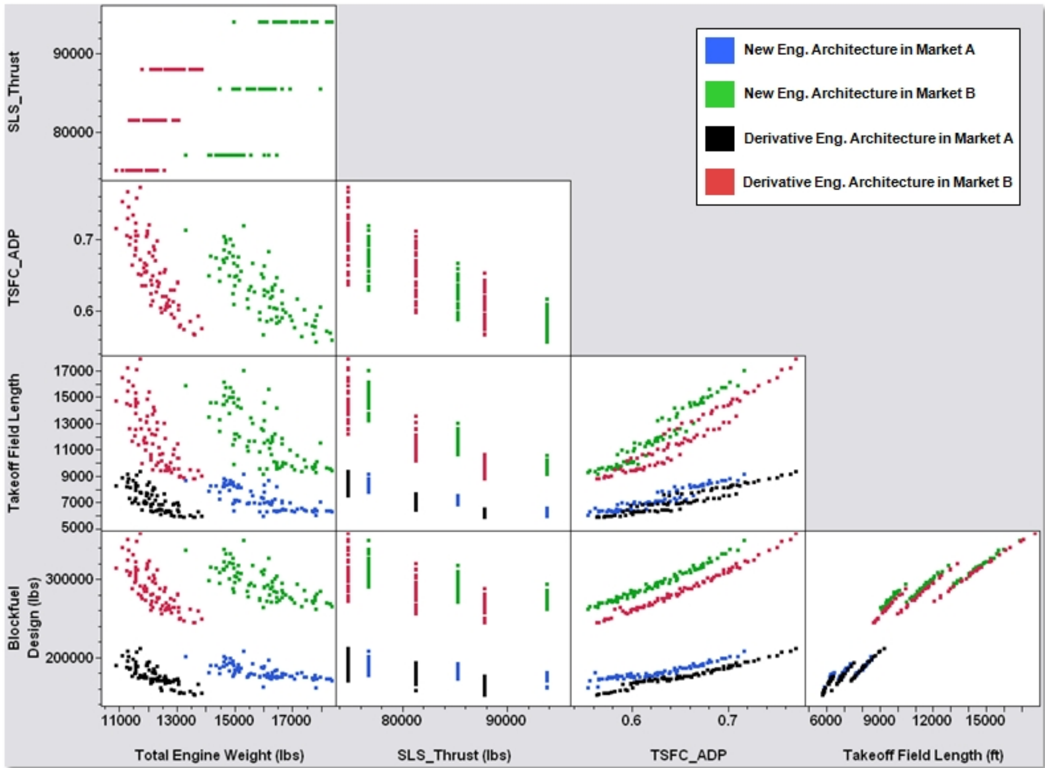

Figure 5.8: Step 2 Engine Design Alternatives Results

The relationship of engine weight and thrust are consistent with the what would be expected as engine weight increases with thrust. The thrust is discretized into three levels as specified in the input. The derivative architecture weighs less but also generates less thrust. Another important verification is the trends between block fuel and TSFC. As TSFC increases the mission fuel burn increases for both architectures. Market B (extended range) has a larger block fuel and is more sensitive to TSFC than market A. The engines are now transferred over the customer value analysis to evaluate them based on the preferences of the airlines.

5.4 Step 3: Customer Value Analysis

The objective of this step is to estimate the value that each engine design will have in the market. In engineering design it is very challenging to model the economics of an airline. Maximizing return to the manufacturer is a difficult calculation in design. There are unknown impact of sales incentives or geopolitics. For this reason, the engineering approach is to attempt to design the engine that maximizes the value to the potential airline customer(s). Rational customers buy engines that provide the "best value" for their business case. Airline customer value is a primary objective function for commercial engine design and is a function of the customer's operating conditions, like route structure and type of aircraft used.

There exists tools like Aircraft Life-Cycle Cost Analysis (ALCCA) that effectively estimate the manufacturing and production costs of aircraft and the operating costs for airlines. Although these tools can be used to understand costs and estimate revenues, as stand-alone tools they are limited in their capacity to effectively determine the value an engine/aircraft combination has to the operating structure of an airline. This research depends significantly on the ability to evaluate engines based on how well they match an airlines operating conditions and their overall business case.

The traditional valuation approach is the Discounted Cash Flow (DCF) method which projects investments and sales to predict the future cash flows of new product. It adjusts the value of future cash flows with a discount rate to obtain the present value which is then added over the time period to obtain the Net Present Value (NPV). The corresponding formula for computing the NPV is:

$$NPV = \sum_{i=0}^{T} \frac{R_i - I_i}{(1+r)^i} \tag{5.1}$$

where R is revenue, I is the investments or costs, r is the discount rate, T is the total time that the product will be in receiving revenues or expending costs, and i is the year. The discounted cash flow is a useful way of evaluating enginering projects in terms of their economic value to a firm.

The NPV result will be determined mainly by the input parmeters r, R, and I. The discount rate, will typically depend on the internal economic status of the firm and can be impacted by the firm's credit history. Since this impact is internal to the engine manufacturer, the fluctuations of the discount rate are beyond the scope of this research. A firm's revenues are directly linked to the market demand and the market share achieved by the firm. Marketshare in turn, is directly a function of the *customer value* which depends on a products' peformance characteristics, operational results and how significant the customer values competing products. A firm will also have to make key investments, particularly in the R&D phase where substantial sunk costs or common for complex aerospace systems. These costs will fluctuate throughout the design, development and production phases as engineers finalize the concept and/or add technologies. Production costs are also driven by labor and production rates which can change independently and is not typically under the control of the firm. For the purposes of valuating an aircraft engine, the key contributors to the NPV are essencially, the producer's discount rates, forecasted sales, and technology selections. Furthermore, the impact of external factors like fuel prices, noise/emissions regulations, maintenance rates, and airline preferences in fleet utilization also affect the customer value.

Step 3 in the methodology provides a way of addressing the first two research questions which seek to discover ways in which the technical design space can be evaluated concurrently with customer requirements. These questions are presented below.

> **Research Question 1.1:** How can the technical design space of complex systems be expanded to model the economic success of R&D programs with uncertain market requirements?
>
> **Research Question 1.2:** How are customer requirements mapped to generate feasible designs and establish value?

The development of a customer value tool is essential to identifying what particular aspects of a commercial engine affect the directly and indirectly the customer value. This tool is described in the subsequent sections.

5.4.1 Customer Value Analysis Tool

An important contribution in this research is the creation of a tool that helps to better predict and understand the value perceived by the airline and the engine manufacturer that is capable of accounting for external factors. The tool is an Excel-based modeling and simulation environment that uses state of the art cash flow analyses to compute the

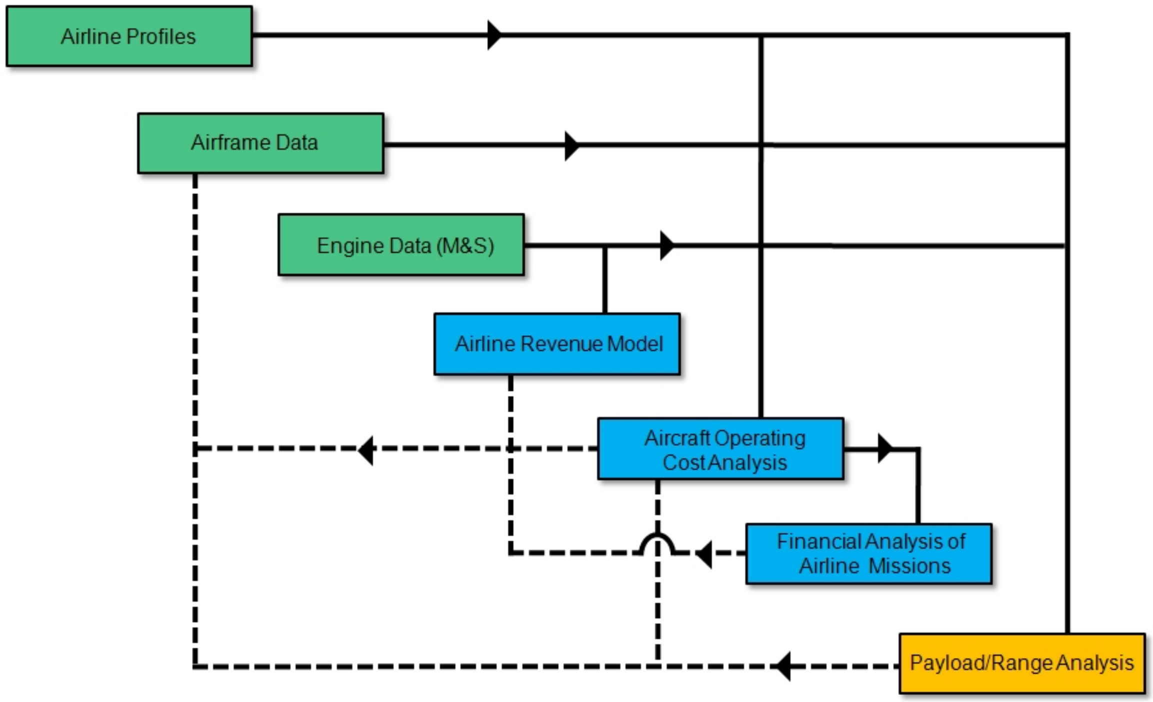

Figure 5.9: Customer Value (Financial) Modeling Environment

economics of the airline. The economics are initially calibrated using data from a various airlines operating the B777-200 and B777-222ER ((Air France-KLM, 2008; The Emirates Group, 2002-2003). The data, based from the airlines annual reports specifies the operating costs per trip for a given city pair route. Although the model is roughly calibrated to some airlines, the focus of this research is in the competitive analysis results. The economic analysis tool provides a means to compute value and can be updated as necessary. The model is composed of a total of 11 worksheets. Three of them are inputs, four contain computations, three are assumptions, and one contains all the results. A schematic of how the different modules are interconnected is presented in Figure 5.9.

Airline Profiles Module

The airline inputs sheet contains information about the five airline customers in the market. A particular aircraft will typically have a variety of missions requirements throughout its life with an airline. These missions are often not similar in range and payload. For instance, airlines often operate the Boeing 777-200ER over a variety of different missions

Table 5.6: Airline Profile Ranges

Airline Variable Name	Ranges
Utilization for missions 1-12	0-100%
Utilization of Aircraft per day (hrs)	15-18
Expected Number of Orders	20-100
Average $/RPM	0.11-0.17
Passenger Load Factors for missions 1-12	0.7-0.98
Cargo Load Factors for missions 1-12	0.7-0.98

and payloads, ranging from 1000 nm to 6000 nm and with payloads of 40,000 to 120000 lbs. Any combination thereof is feasible, provided that fuel volume and takeoff weight limits are met. Mission mixes potentially have a large impact on engine design since they are expected to perform optimally during every mission scenario. Further, airlines do not fly each mission equally every year. A vector of aircraft utilization for each mission is presented in table 5.6 both market A and B, for each airline. These values are on a scale of 0 to 100 where 100 indicates that that range is representative of common city-pair routes for that airline.

Five airline profiles are created based on the ranges from table 5.6 and are used to represent different demand segments in the market. To better visualize how the utilization vector varies with each airline profile, the payload/range diagrams are illustrated in Figure 5.10 for both the base-range airframe and the extended range airframe. The difference between airlines 1 and 5 is in the way they utilize the airframe for their routes. Airline 1 has the most frequency of trips (per year) with ranges below 2000 nautical miles. Whereas airline 5 bulk of operations are towards the 6000 nautical miles range and above. The purpose of having two available airframes to choose from enables the airlines to optimize their use of the airframes capabilities. Airline 1 is likely to prefer an engine that matches well with the market A airframe and airline 5 will likely select market B. The choice of airframe and engine that suits the airline will translate to more efficient operating costs for the airline. In return this airframe/engine combination will be more attractive to the airline and have a higher *value*.

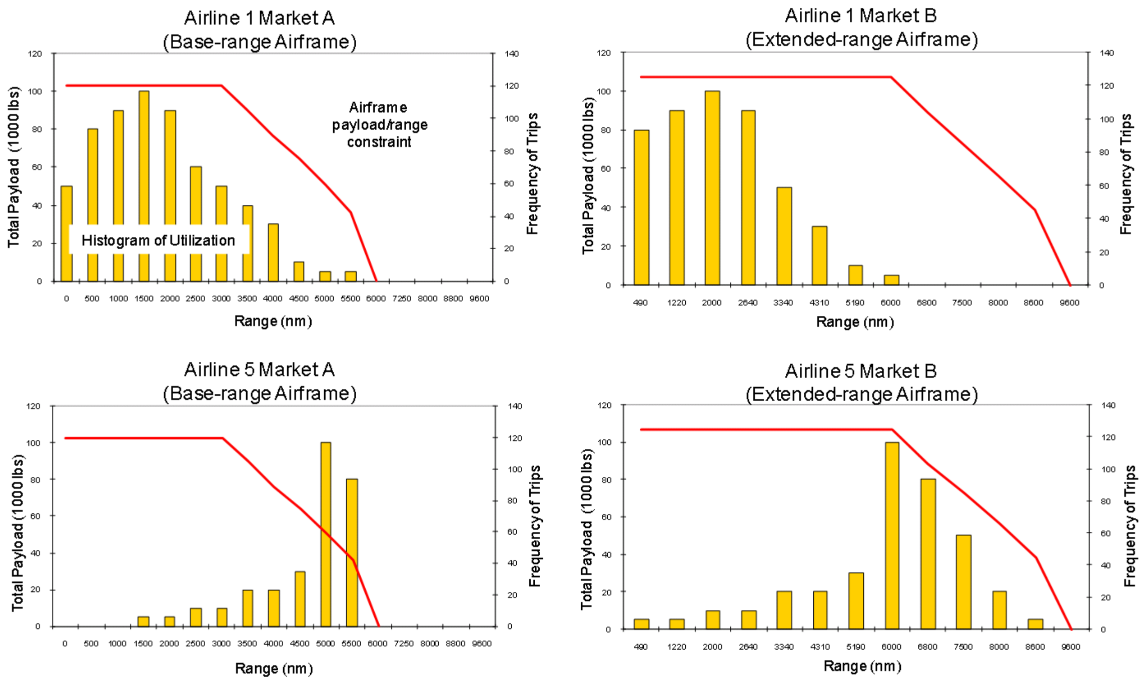

Figure 5.10: Payload-Range Diagrams with Utilization Frequency for Airlines 1 and 5

Airframe Data Module

The airframe data specifies the characteristics of the airframes used for markets A and B. Some of the essential data required for the analysis program include the aircraft empty weight, its maximum zero fuel weight, maximum takeoff weight, and maximum fuel capacity. Most of this information will remain fixed since the focus of this study is not to define the shape of the aircraft but to install the engines that provide the maximum value to the customer for different customer route preferences. Some of the values, such as block fuel for the design mission, will vary based on the engine design. Figure 5.11 presents a snapshot of the user interface for this module.

Engine Data Module

A list of all the engines resides in this sheet. All the engine results from the each of the four DoE's is listed in this sheet. This sheet also computes some preliminary results such as engine manufacturing cost and a first guess on engine price based on historical data. The engine price regression analysis is discussed at the end of this step.

Aircraft Description	MARKET A			MARKET B		
	Design Range	8600 nm		Design Range	Fuel nm	
A/C TYPE	Commercial Airliner of 300-368 Passengers			Commercial Airliner of 300-368 Passengers		
YEAR OF ECONOMICS		2006			2006	
Airframe Description		Weights (lbs)	Totals		Weights (lbs)	Totals
	Manufacturer Empty Weight	288,500		Manufacturer Empty Weight	292,000	
	Total Seats	301		Total Seats	301	
	Total Airframe Weight		288,500	Total Airframe Weight		292,000
Airframe Operating Empty Weight						
	Crew	2090		Crew	2090	
	Unuseable Fuel/Oil	1221		Unuseable Fuel/Oil	1221	
	Std & Op Items	8309		Std & Op Items	8309	
	Total AOEW		300,120	Total AOEW		303,620
Engine Description	Engine Type	2	(New=1, Der=2)	Engine Type	2	(New=1, Der=2)
	Weight per Engine	16275		Weight per Engine	16275	
	Engines per A/C	2		Engines per A/C	2	
	Engine Sea Level Thrust	0		Engine Sea Level Thrust		
	T4 at SL Thrust ®	0		T4 at SL Thrust ®		
	SFC @ TO	0.056		SFC @ TO		
			32,550			32,550
	Data Using Design Mission 12			Data Using Design Mission 12		
Zero Fuel Weight						
	Passengers LF			Passengers LF		
	Passengers weight (lbs)	63,210		Passengers weight (lbs)	63,210	
	Cargo LF			Cargo LF		
	Cargo weight (lbs)	(0)		Cargo weight (lbs)	(0)	
	MAX ZFW	420000		MAX ZFW	430000	
	ZFW (lbs)		395,880	ZFW (lbs)		399,380
Takeoff Gross Weight						
	BlockFuel (lbs)	255,718		BlockFuel (lbs)	255,718	
	Max Fuel (lbs)	207000		Max Fuel (lbs)	304500	
	MAX TOGW (lbs)	545000		MAX TOGW (lbs)	656000	
	TOGW (lbs)		651,598	TOGW (lbs)		655,098

Figure 5.11: Airframe Description for Markets A and B

Airline Revenue Module

The Airline Revenue Module (ARM) utilizes the DCF method to obtain the NPV of flying the aircraft/engine combination using the utilization distribution previously defined over a period of twenty years. For this calculation, it is assumed that the aircraft is leveraged at one hundred percent, with an interest rate of 6.5% and a term of 15 years. During this period, the airline assumes a ticket price inflation of 3.21% versus a cost inflation of 3.25%. Passenger revenue is obtained by multiplying the $/rpm already defined in the airline profile module by the trip mileage, and the number of passengers flying in the airplane in one year.

Cargo revenue uses a different metric, the cost per pound of cargo per mile. A separate study was performed evaluating comparable prices of cargo transport services on a per-pound basis. The result indicated that as the range of the mission increases, the cost per-pound per mile decreases. However, it was found that for very short distances it was impossible to justify high prices, since for short distances transportation alternatives for cargo are widely available. After regressing the data to create a model of the cargo prices using an exponential function, an adjustment was made to prevent cargo prices to rise so significantly for short

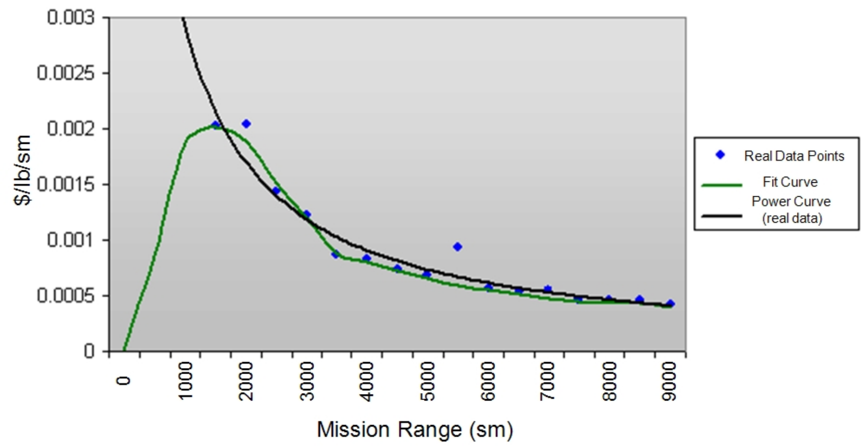

Figure 5.12: Revenue Cargo Prices

routes. Figure 5.12 illustrates the real data based on the Excess Baggage Company (2007) and the curve fit that corrects for the error in short distances labeled Fit Curve.

Total Aircraft Related Operating Cost Module

The Total Aircraft Related Operating Cost (TAROC) is a module that based on the ALCCA cost analysis and converted into and Excel spreadsheet. It calculates the total operating cost per mission and per year with inputs like utilization introduced previously. It includes a graphical interface of the utilization distribution of the twelve airline missions which enables the user to manipulate the profile style of airline they wish to model. In this research study, the utilization distributions per mission for the five airlines are input directly into the appropriate cells. These utilization levels are all normalized with respect to each other to avoid confusion among different values. In this way if all utilizations are set to the same value, regardless of the actual value, the amount of total time available in a year will be equally distributed to all missions. This would cause shorter missions to fly more often than long missions, but the total amount of time allocated to each mission would be the same. The mission mix of two example airlines are illustrated in Figure 5.10.

Payload/Range Module

One of the main benefits of this customer value tool is the flexibility of swapping engine designs to compute the benefits and costs to the airline. The payload/range module allows

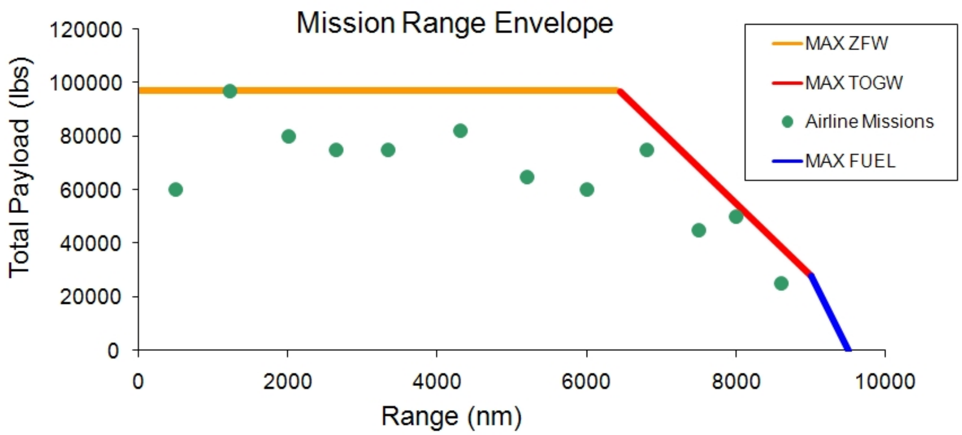

Figure 5.13: Mission Mix Sample and Payload-Range Envelope

the user to visualize the impact of an engine design on the mission and economic performance. The engine will impact the several criteria, including block fuel, cargo revenue, and maintenance cost. The flight envelope sheet enables the visualization of the impact of an engine design on the capabilities of the airplane as a whole. For instance, a light engine will impact the amount of payload available for cargo due to a reduction on total empty weight. As a result, the potential revenue produced by cargo will increase. A similar effect is observed if an engine has a lower block fuel requirement for a specific mission. An iterative calculation takes place with up to one hundred cycles to converge on a solution of required block fuel for each of the missions. The envelope, illustrated by the colored lines in Figure 5.13, changes dynamically with different engines. The top constraint is the maximum zero fuel weight. This limit is set by the maximum stress that the wings can support due to bending moment if all the weight is accumulated in the fuselage and there is no fuel on the wings. This line does not change with different engines, but it sets the maximum amount of cargo weight available after the fuel and passengers are included. The red line illustrates the maximum takeoff gross weight of the aircraft. This limit is set by the airframe manufacturer and therefore does not change with different engines. However, the position of this line will migrate with different engines. As a new engine becomes more efficient, it is possible to load more payload and less fuel, increasing the range of the airplane. It's slope is downward due to the tradeoff between fuel and cargo. The intersection between the maximum zero fuel weight constraint and the maximum takeoff gross weight is achieved by loading the airplane

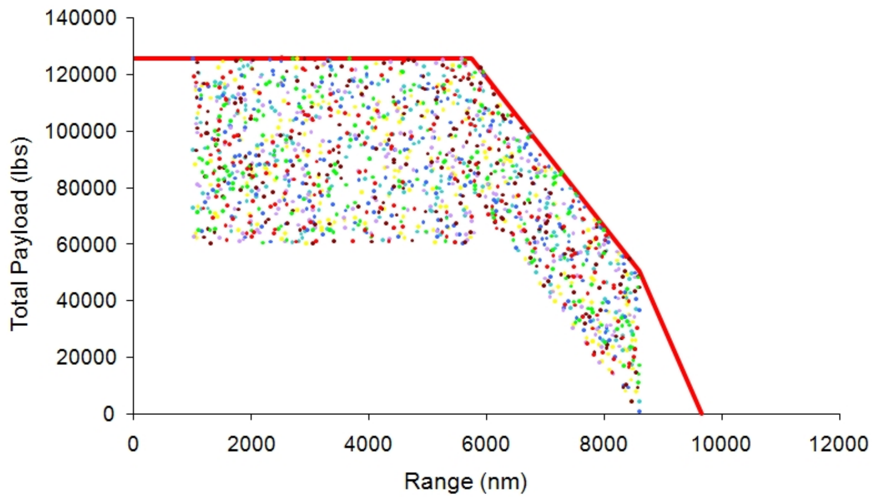

Figure 5.14: Mission Mix Inputs for Block fuel Regression

to its maximum capacity in terms of passengers and payload, and then increasing the fuel level available until MTOGW is reached.

Longer range missions will require a trade-off between fuel and payload to ensure that the MTOGW constraint is not violated. Eventually, once the fuel capacity is reached, the only way to fly farther routes is to decrease the passenger or cargo payload and make the airplane lighter. This is case is shown by the blue line in Figure 5.13. However, the airlines analyzed in this research do not fly missions in the extreme range of the flight envelope.

The script that runs the customer value model uses Excel solver functions to iterate on block fuel calculations until a balance between fuel required and fuel available is achieved for each mission. In addition, every time that a new engine design is selected for this module, the flight envelope and payload load of each of the missions adjusts to ensure they stay within the constraints using the load factors specified by the airline inputs.

As a final note, the mission mix flexibility (different airline payload/range profiles) of this module is possible because of the inclusion of a surrogate model for block fuel. Block-fuel is regressed against the engine design variables as well as values of range and payload that bound the payload-range design space as shown in Figure 5.14 . Each point shown is run through the FLOPS module in the EDS environment to calculate the block-fuel required for that payload range combination.

5.4.2 Computing Project Value

The customer value tool provides the engineer with the economic results for each engine design for the five airline customers outlined previously. The final part of step 3 is to assign every engine design a *value* based on the importance that each airline gives to specific metrics of interest. As described in section 5.4, there are several possible methods that are capable of ranking the engines based on the importance of certain criteria to the airline. Since the focus of this research is primarily on the competitive analysis, a weight-based OEC was used to evaluate each engine alternative against specified airline criteria.

The first step was to down-select specific criteria that would be useful to distinguish engines in terms of the their economic and technical performance. At the same time the goal was to focus on criteria that would be significant to the business case of the airline. In the latter case, a revenue/cost approach was taken and a discounted cash flow with net present value became the representative criteria to use for the economics. On the revenue side, it is possible to track how the different engine weights and block fuel requirements affect the passenger and cargo payload potential and thus impact the revenue potential. On the cost side, the engine price was computed by regressing existing engine price data from similar engines in production today as a function of thrust, TSFC, fan diameter, and engine weight. An important factor to airlines is the maintenance cost and this is calculated based on the ALCCA maintenance module. Maintenance cost per hour (MCPH) is computed based on several engine characteristics, like maximum turbine inlet temperature (T4), material selections, etc.

The three criteria chosen to compute value are: airline NPV, MCPH, takeoff field length. These three metrics were chosen at the outset of the investigations and a sensitivity analysis was performed to determine which of the three had more leverage on customer value. Takeoff field length was selected as a criteria because all five airline profiles were assumed to operate from different airport locations and thus different runway lengths. However, both NPV and MCPH had a larger impact on the value results. The MCPH calculation was separated from the cash flow analysis in order to visualize the impact of NPV and MCPH separately. All three criteria were used initially with an OEC where all the airlines had equal weights

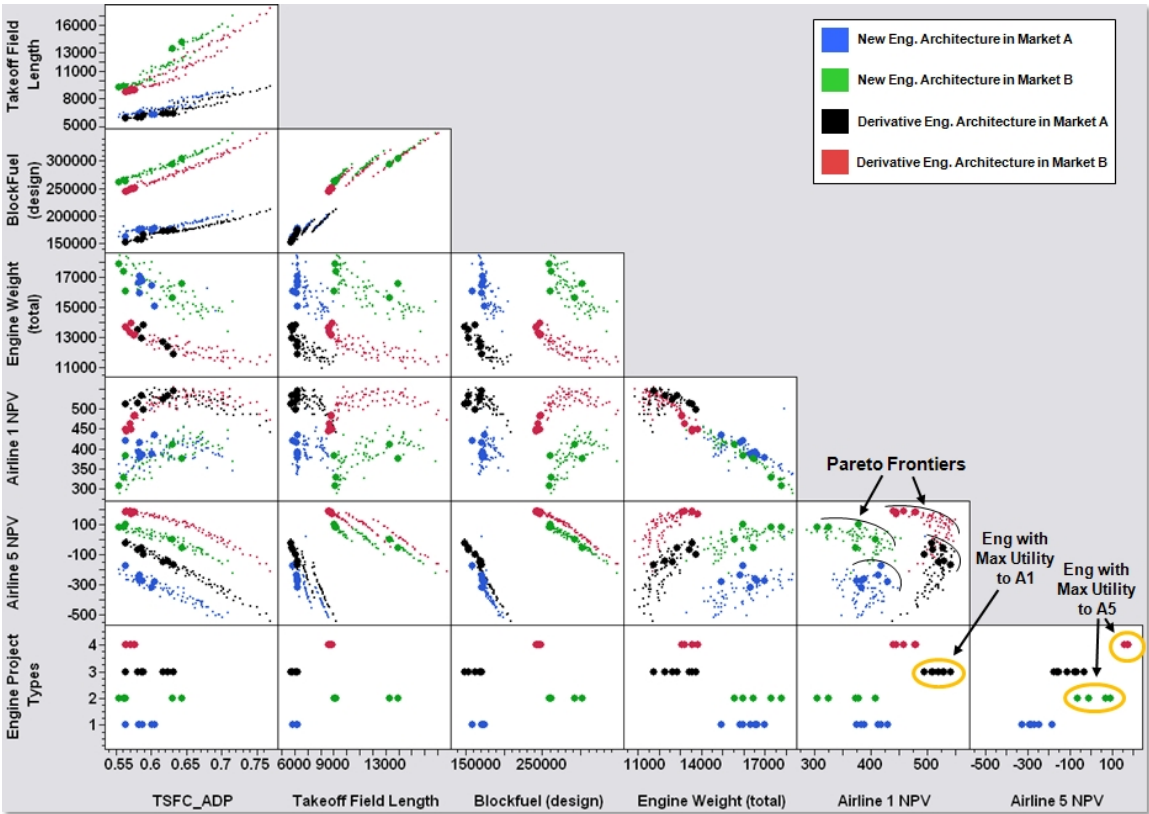

Figure 5.15: Combined Engine and Customer NPV Pareto Filtered Results

(preferences) for each criteria. The ranking of engines varied mostly with NPV. Therefore, MCPH was rolled back into the NPV calculation and NPV was chosen as the only contributor to customer value. This action was taken primarily to simplify the analysis of the competitive results in steps 4 and 5. But it's important to note that several studies were made with varying airline criteria preferences. Finally, this area can be revisited in the future to include other significant airline criteria.

The result of step 3 is a ranking of all the engines for both new and derivative projects based on their customer value. This ranking will be used to compete the engines in the market with the other firm. A market share value will be assigned to each firm based on how well their engines perform against each other. To subject of computing the market share and the subsequent payoffs to each firm is the subject of step 4.

5.5 *Step 4: Evaluate Projects*

The proof-of-concept now proceeds with a competitive analysis of the projects and their engine alternatives. The first step is to compute the market shares for each firm based on the customer value analysis in the previous step. The result will be a market share matrix that will then be used to compute each firm's payoff for each project and engine alternative. These payoffs are a function of several criteria, particularly including the market scenarios outlined in the project roadmap of step 1. These market scenarios determine which firm is the leader and follower into the market. A payoff matrix is generated and is carried over to step 5 of the methodology for the competitive analysis and down-selection of the engines. The reader is referred back to section 5.5 and Figure 4.11 as a reminder to the hierarchic structure of projects and design alternatives.

5.5.1 Market share Calculations

The market share matrix, defined in section 4.2.4.3, is populated through an algorithm that competes a firm's engine design against another firm's engine based on the engine value to the airlines. There are 81 engine alternatives for each of the four project/market combinations: new-market A, new-market B, derivative-market A, and derivative-market B. The algorithm first filters the engines within each project by selecting the best engine (max value) among the three thrust levels. This is consistent with how an engine manufacturer would design an engine for a particular airframe. They would determine which of the three thrust levels is best for a specific airframe and only offer that thrust level to the market. Figure 5.16 presents the algorithm for computing market share.

This thrust filter reduces the amount of engines from 81 to the top 27 engines. The 27 engines of market A are competed against market B's engines and the the 7 best engines of each market are selected. The point here is not to remove a market option completely since there may be some airlines that prefer one market over the other. The same approach is taken for the next project type and the entire process is repeated for firm 2. An important note to make here is the assumption in this research that the game between these two firms is symmetric. Therefore, for the purposes of this proof-of-concept, the 28 engines selected

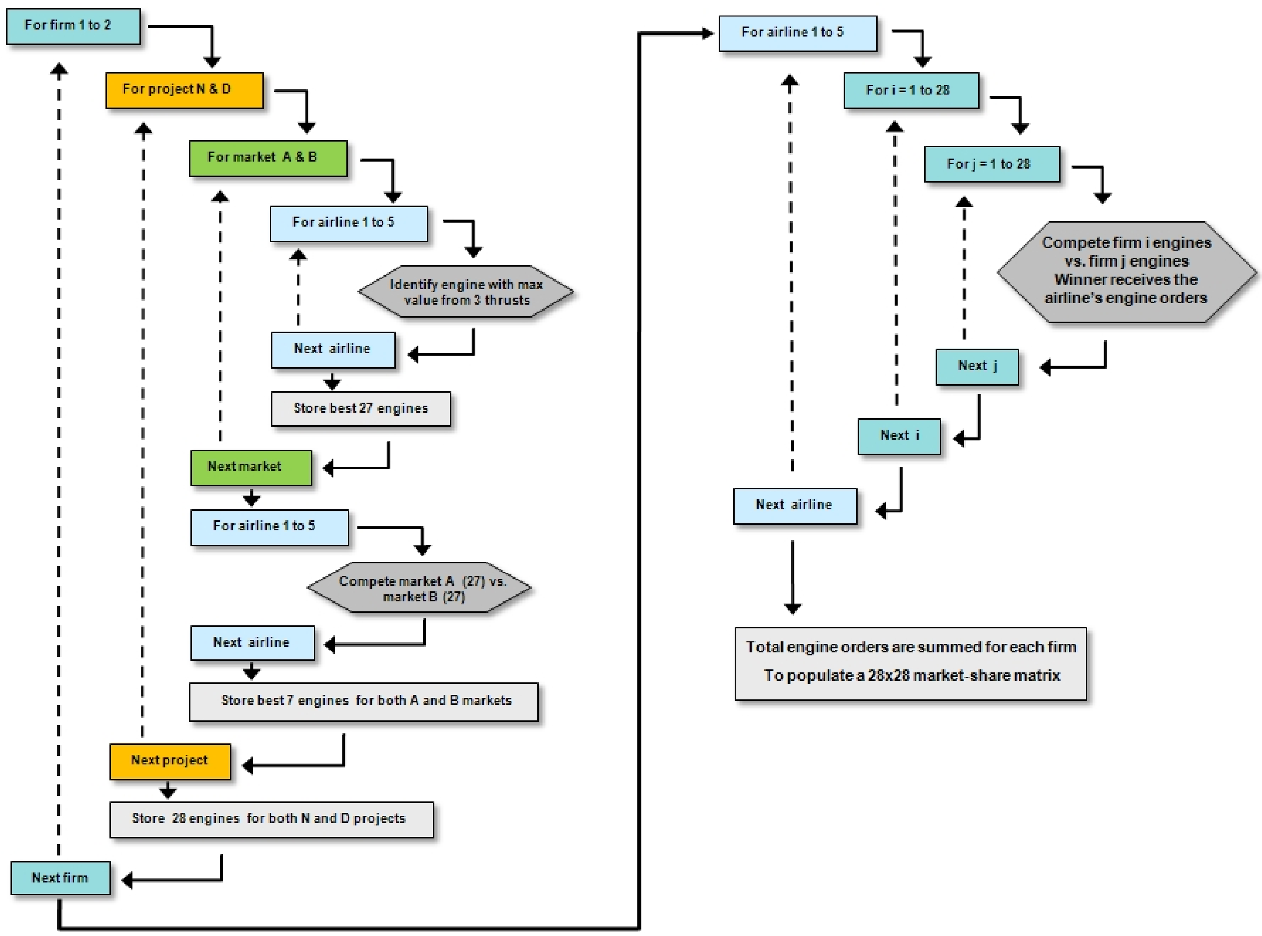

Figure 5.16: Algorithm to Compute Market Share

Firm 2

Firm 1			N A 31	N B 55	D A 65	D B 27
N	A	31	50 50	20 80	60 40	80 20
N	B	55	80 20	50 50	80 20	60 40
D	A	65	40 60	20 80	50 50	40 60
D	B	27	20 80	40 60	60 40	50 50

Figure 5.17: Market-share Matrix

for firm 1 are the exact same engines selected for firm 2. The resulting market share matrix, as expected, will show a 50% share to each firm along the diagonal of the matrix.

The market share itself is computed based on the number of engine orders won by each firm. A reminder here is that market share is only based on the customer value via engines sold. The resulting 28 by 28 matrix is reduced one last time to a 4 by 4 matrix, shown in Figure 5.17, by selecting the top ranked engine for each project-market option. The numbers beside each project-market option identify each engine from the list of 81 engines in the DoE. The colors in the cells engine ID cells reflect the thrust level for that engine. The benefit of tracking the engine ID through the entire process is observed at the end where it will be possible to connect the choice of architecture with specific engine cycle parameter settings.

There are several reasons for reducing the matrix down to a 4 by 4. After analyzing the 28 engine options (7 for each project-market) in the matrix through the entire methodology for various airline preference variations, the equilibrium results in step 5 showed that in 95% of these airline preferences the top ranked engine for each of the four options was the same. The computation of the Nash equilibrium of a 28 by 28 matrix game takes about 15 times longer than for smaller matrices. For the purposes of this research, the objective is to down-select engines in an intelligent manner and maximize the transparency of the decisions made in down-selecting those engines. Therefore, since the proposed framework is capable of tracking these down-selections, it is possible in the future to analyze any size matrix when faster computation capabilities become available. The second part of this step is to compute the payoffs to each firm for every project-market option they have.

5.5.2 Project Payoff Calculations

The project payoff calculations are made with two primary inputs, the project completion time for each firm as well as the market share data determined by the customer value in step 3. An important assumption prior to completing the payoff analysis is to make sure that all the potential engine designs are technically feasible. This verification process is made in step 2.

The engine manufacturer payoff calculation is made via a financial tool developed by the author using the ALCCA analysis framework to assess the revenues and costs associated with developing an engine. As stated earlier, it is impossible and impractical to assess the accuracy of this model since neither the model nor the data it produces are publicly available. The value added to the design process relies in the fact that the behavior of this model is similar to that of real life models, since they are all driven by the basic laws of finance. Also, the fact that this model is not calibrated against any set of real data or other revenue model does not impede the engine comparison process from an economic perspective. This is because any estimation error embedded in this model would affect all designs in an equal manner since the amounts by which the financial solutions differ from reality would be roughly the same for all estimations.

The engine payoff model employs a discounted cash flow model similar to the one developed for the airline. The main difference is that whereas the airline model uses passenger and cargo revenue and operating costs to obtain a NPV, the engine manufacturer model has two different sources of revenue. The first source of revenue comes from the sales of the engine itself. The engine sales are determined directly from the market share matrix. In the recent years the business model of engine manufacturers has shifted from being sales-centric to more customer service-oriented. Engine manufacturers attempted to become profitable

Firm 2

Firm 1			N		D	
			A	B	A	B
			31	55	65	27
N	A	31	64 146	23 185	89 26	68 89
N	B	55	59 11	61 154	46 6	79 12
D	A	65	26 240	26 240	213 29	101 36
D	B	27	67 159	6 285	340 6	264 36

Figure 5.18: Payoff Matrix for One Market Scenario

by selling high quality engines with high upfront costs. As a result in today's market engine prices have dropped relative to historical prices, and the business focus has shifted to providing strong maintenance contracts to ensure a stable source of revenue over the years and reduce, in this way, market fluctuations produced by weak sales periods. The second source of revenue of the ERM is therefore produced by maintenance contracts. Some of the assumptions of the maintenance model include:

- A maintenance contract period of ten years after the engine is delivered
- An additional 10% of demand is produced for spare engines
- The normal production rate of engines per year is about 250
- Maintenance overhead is approximately 200%
- Maintenance cost per hour is approximately 10% of the actual cost paid by the airline

The structure of the payoff is based on equation 4.10 for each project of each firm. The financial tool described previously is formulated based on this equation and the payoffs are computed as described in section 4.2.4.3 in Chapter 4. The result is a payoff matrix as shown in Figure 5.18

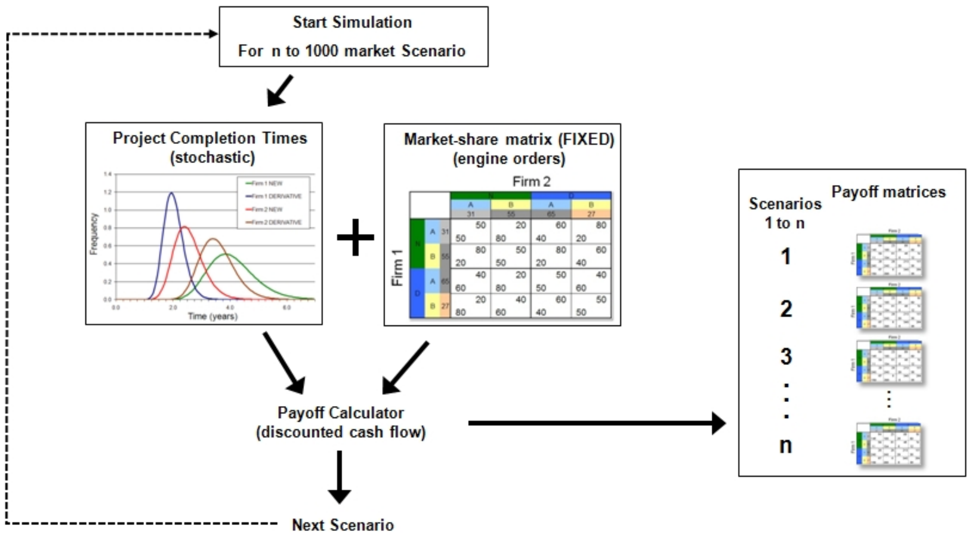

Figure 5.19: Firm Payoff Simulation Algorithm

Since there is uncertainty surrounding the completion of engine R&D programs, a simulation of PCT's is warranted to address the schedule uncertainty. The simulation of payoff matrices is performed for different samples of PCT's and the algorithm is shown in Figure 5.19. These are referred to as different market scenarios. For each market scenario a project completion time is sampled from the log-normal distributions for each firm and for each of their project types. These distributions can be constructed to simulate the knowledge and expertise a firm has when it develops a new or derivative engine. When GE and PW were determining which engine architecture to develop for the Boeing 777 program in the late eighties they had to base their decision primarily on the existing technologies and engine cores they had available. The purpose of having a distribution of project completion time that is different for each firm is to model the differences in the way each firm develops particular engine projects and reflect that through a target project completion time. Figure 5.20 illustrates the proposed project completion time distributions for each firm and their two architecture types. The choice of a log-normal distribution is made to reflect the fact that engine manufacturers will typically have a target date for the completion of their engine development. This target date is represented by the mean of the distribution. In most cases however, that target date cannot be confirmed with certainty and there is a higher likelihood that the date migrates to the right of the distribution than to the left. In other words, if

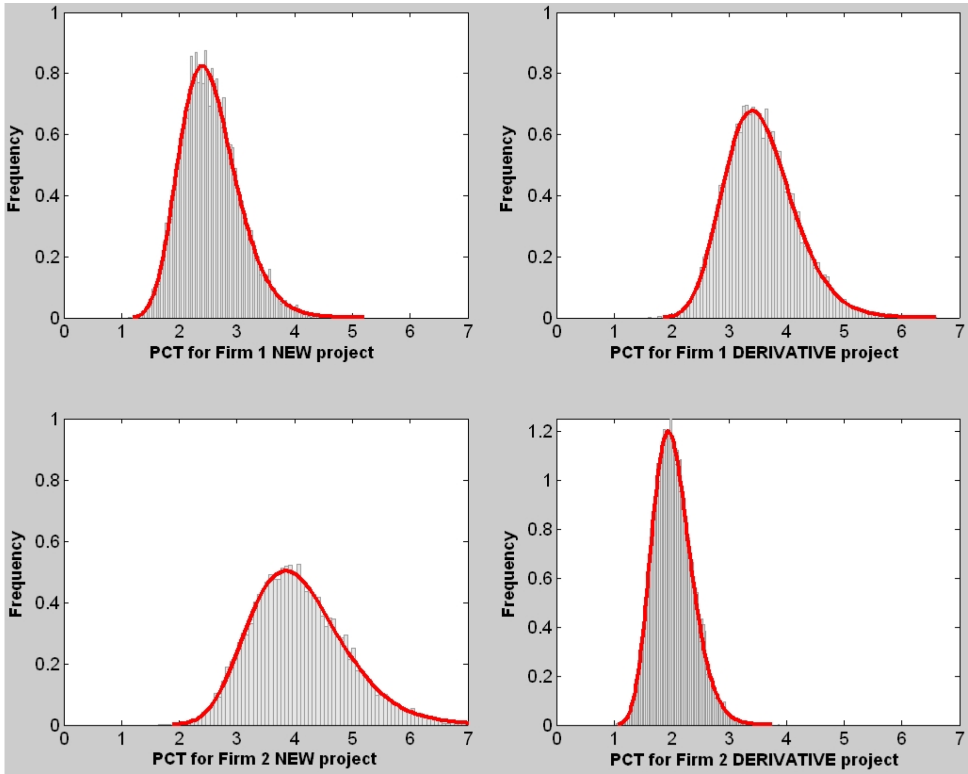

Figure 5.20: PDF's of Project Completion Times for Payoff Simulations

firms cannot meet their target date, the result is that is probably going to get pushed back rather than pushed forward. This is evident in the development of several current R&D aerospace projects like the Boeing 787 and Airbus A350-XWB.

After having generated all the payoff matrices for all the 1000 market scenarios the next step is to down-select an engine that is strategically positioned to maximize the return to the manufacturer. This down-selection will be enabled by a competitive equilibrium analysis.

5.6 Step 5: Strategy Valuation and Down-Selection

The payoff matrix generated in step 4 is an important result in this research. It specifies the return on investment (in terms of NPV) for the engine manufacturer based on the engine project they decide to undertake for development. Before making any engine selection it is important to revisit the problem definition in step 1 to restate the goals and key characteristics of the proof-of-concept. The QFD analysis highlighted the key technical targets for the engines in terms of cycle parameters. It also provided a sense of what the schedule requirement would have to be for the completion of a engine for the 300 passenger aircraft. Those results bounded the direction of the proof-of-concept and therefore the resulting engine options available with their associated payoffs are a product of the "rules" specified in the problem definition.

An engine selection decision must be made with respect to many influential factors. There are two primary factors studied throughout this implementation problem, the market-entry uncertainty of engine projects and uncertain competitor behavior. They each impact the payoff a firm will receive. The first part of step focuses on evaluating uncertain competitor behavior and identifying strategies to selection an engine the competition in mind.

5.6.1 Computing the Nash Equilibrium

The game structure matrix of alternatives in step 1 specified the rules of the game for the proof-of-concept. The reason for specifying the way in which the game is played is to select the correct game theoretic technique that will compute the game equilibria. The game structure for equilibrium-calculation purposes is defined as a normal form game where two players select engine projects simultaneously. In section 4.2.5.1 of the methodology formulation, the process for computing the game equilibria was described. The reader is also referred back to Chapter 3 for a broad review of useful game theory techniques for these types of applications.

The Nash equilibrium calculation specifies what the optimal solution of the game will be for both firms. By relying on the equilibrium result, firms will be guaranteed to not do worse than if they were to select a different engine strategy. This assumption holds only when both players can conclude rationally, that this result is optimum for them. However, the subject of irrational decision-making, albeit beyond the scope of this research, is introduced in the next subsection which introduces the element of risk in selecting engines.

The equilibrium of the payoff matrix generated in step 4 (Figure 5.18) for a discrete (fixed PCT's) market scenario, with the following assumptions is shown in Figure 5.21. This payoff matrix is based on the market share matrix calculated in step 4 and the following discrete project completion times and first/second mover advantage parameters:

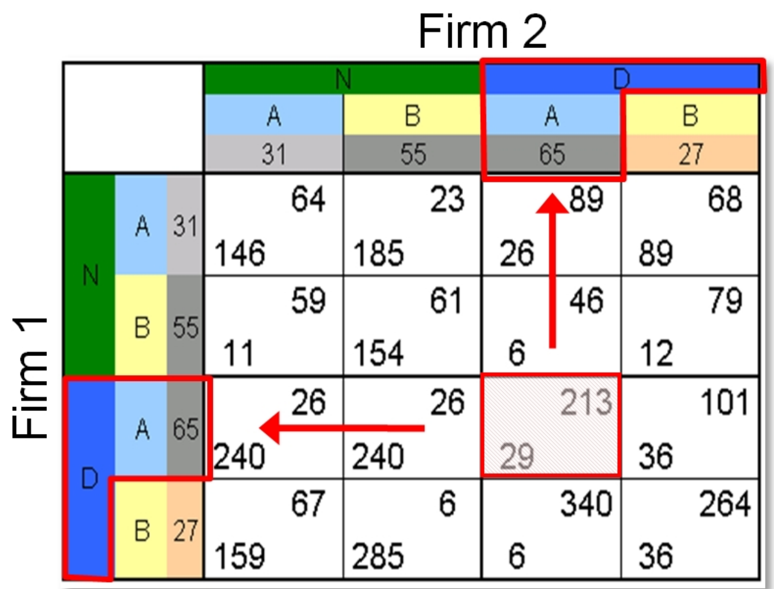

Figure 5.21: Payoff Matrix with Nash Equilibrium Solution

- PCT firm 1 *new* engine project (T1N): 2.5 years
- PCT firm 2 *new* engine project (T2N): 4 years
- PCT firm 1 *derivative* engine project (T1D): 3.5 years
- PCT firm 2 *derivative* engine project (T2D): 2 years
- When both firms develop *new* engines, leader receives (α_{NL}): 50% of duopoly rewards (equal advantage)
- When both firms develop *derivative* engines, leader receives (α_{DL}): 50% of duopoly rewards (equal advantage)
- When both firms develop different engine architectures, *new* leader receives (σ_{NL}): 50% of duopoly rewards (equal advantage)
- When both firms develop different engine architectures, *derivative* leader receives (σ_{DL}): 50% of duopoly rewards (equal advantage)

These assumptions are the market scenario parameters that determine how the payoff (rewards) for each period (monopoly and duopoly) are distributed among the two firms. In this very first result, the objective is to start from an equal distribution of rewards to observe the impact of PCT's only. Introducing different values for the first/second mover advantage parameters would skew the results and it would become difficult at first glance to differentiate the effects of PCT's on the Nash equilibrium (NE) result.

The NE result in Figure 5.21 implies that both firms should develop a derivative engine for a market A (base-range) airframe. Firm 1 would receive a payoff of 29 and firm 2 would receive a payoff of 213. The main reason why firm 2 receives a higher payoff is because it enters the market first as a leader and enjoys monopolistic rewards for the first two years (T1D = 4, T2D = 2) before firm 1 enters in year 4. It is important to note however, that all the payoffs are a function of both market timing as well as market share (function of customer value). The NE result is more of a recommendation to firms. It is difficult, if not impossible, for a decision-maker to look at the payoff matrix and determine an optimum choice of engine. The advantage of having the NE mechanism is to recommend a solution when there are two many options to down-select from. Although the NE solution is not payoff-dominant for either player (both players could do better payoff-wise but with more to lose), it is an optimal solution that maximizes the return on investment, no matter what engine the opposing firm decides to develop. Playing the NE strategy can be viewed as a risk-averse approach where each firm can do no worse if they maintain that strategy.

5.6.2 Firm PCT Simulations

The next step is to evaluate the results of different market scenario simulations. Here we introduce the notion that there is uncertainty in the PCT of each project. A single payoff matrix with a fixed PCT alone is not enough to make a robust engine selection. PCT simulations provide decision-makers with a broad spectrum of potential situations of different completion times between projects so that they can make a more informed strategic decision as to which engine architecture to develop.

The results are generated based on the firm payoff simulation algorithm described in Figure 5.19. For each firm there are four possible engine choices: New in Market A, New in Market B, Derivative in Market A, and Derivative in Market B. The results in this dissertation are presented from firm 1's point of view. So for example, if the equilibrium

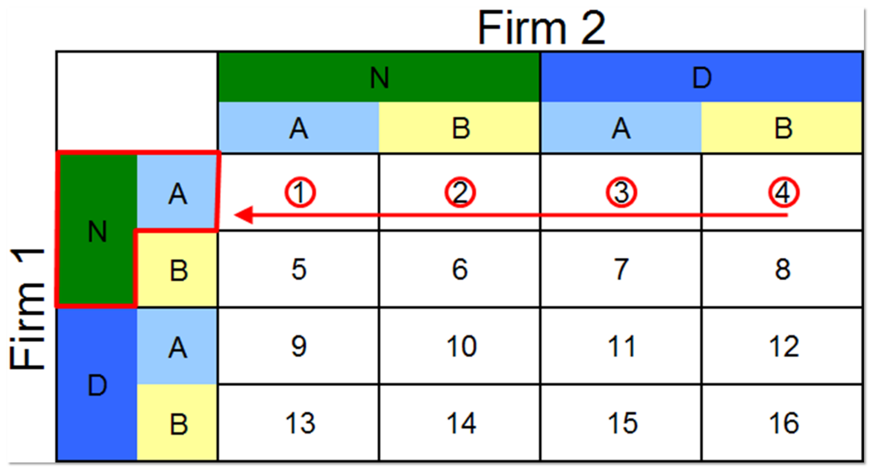

Figure 5.22: Firm 1 Strategy Selection as a Function of Equilibrium Location

point is located in any of the cases 1, 2, 3 or 4 shown in Figure 5.22, then the choice to firm 1 is the same, namely, new engine in market A. Likewise, if the equilibrium is located within cases 5, 6, 7 or 8, the resulting choice for firm 1 is a new engine in market B. A similar approach could be taken from Firm 2's perspective where cases 1, 5, 9, and 13 all correspond to Firm 2 choosing a new engine in market A. This approach facilitates the visualization of equilibria by only considering one firm at a time.

The market scenario results from the payoff algorithm are illustrated in Figure 5.23. The multi-variate plot shows firm 1 and 2's new project completion times as a function of the Nash equilibrium location in the payoff matrix. The numbers on the matrix location axis correspond to the game cases in shown in Figure 5.22. Based on the assumed PCT log-normal distribution assigned to firm 2's projects, it is possible to deduce from the market scenarios which engine strategy firm should undertake. If firm 1 can estimate that it can develop and introduce a new project within 4 years or less then it should commit to a new project. However, if it believes that its new project will take 4 years or longer to develop, it should switch and undertake a derivative project instead. Furthermore, if firm 1 stays with a new project strategy, it should focus entirely on market A. If however, firm 1 pursues a derivative project, it should focus primarily on market B. It interesting to note that when a new engine strategy is optimal, targeting market A is more profitable and when a derivative engine is optimal, market B is more profitable. These results are not entirely

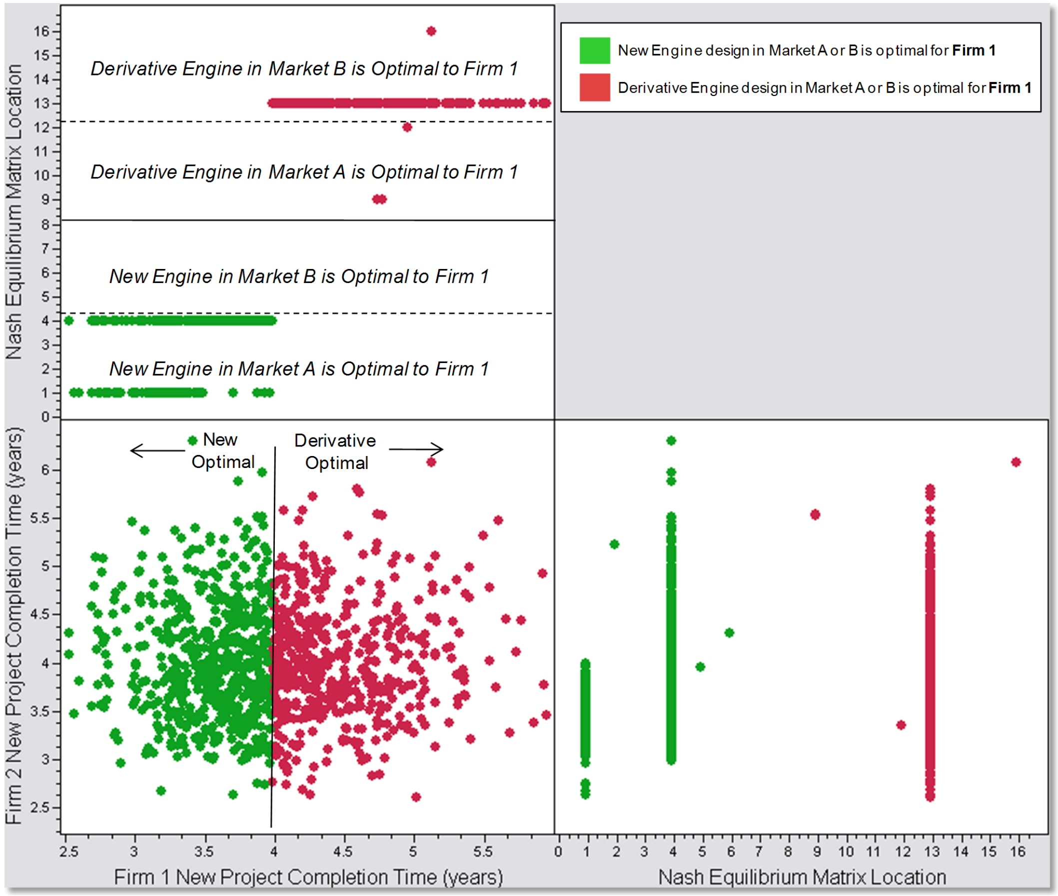

Figure 5.23: Multi-variate Plot of PCT's for Firm 1 and 2 Illustrating Optimal Project Selection

intuitive since one might expect a new engine architecture to satisfy longer range (market B) aircraft missions because of its higher thrust potential. However, its important to note that these results are not simply based on the technical performance of each engine. The payoffs are driven also by the airline economics and how well each engine/airframe satisfies the airline requirements. In these results, a derivative engine, albeit with less thrust potential, is optimal for airlines that operate in long-range missions. In some cases, firms do not intend to capture diverse segments of the market but instead focus on targeting specific airlines. This information would then be fed back into this analysis so that more weight is given to those specific airlines that operate in either base-range or long-range missions.

A look at the variability of the PCT distribution for new project reveals a dispersion of market scenarios along the PCT axis. The same payoff algorithm is run three separate times for different values of sigma new, the standard deviation parameter of the log-normal distribution. Figure 5.24 shows the inputs for that study. The resulting market scenarios

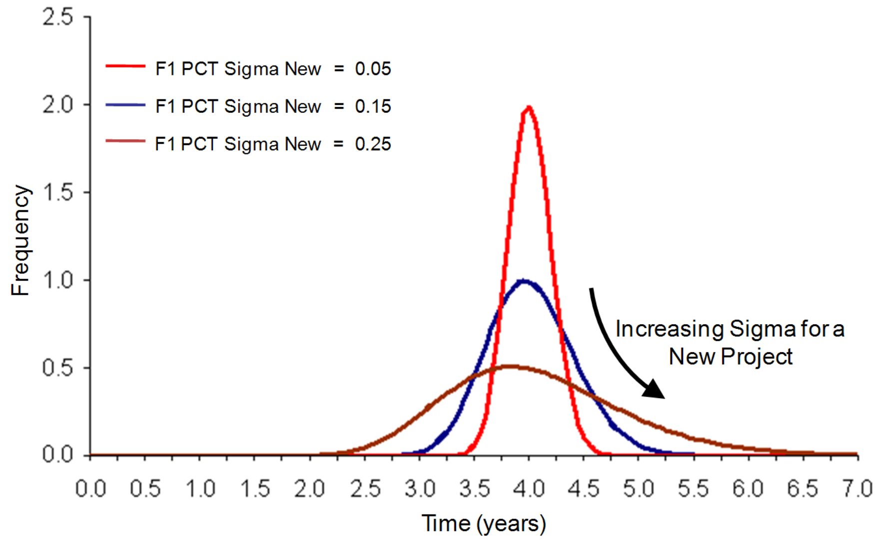

Figure 5.24: Increasing the Standard Deviation of the PCT Distribution of a New Project

are shown in Figure 5.25. The top grouping corresponds to a PCT distribution with a sigma value of 0.05, the middle set corresponds to a sigma of 0.15 and the bottom set corresponds to a sigma value of 0.25. These results show that changing the variability parameter of the PCT distribution only impacts the dispersion of the market scenarios and not the project "switch line". It is worthwhile to note that the shape of the log-normal distribution has a direct link to the dispersion of the market scenario results. The primary interest however, is the project selection decision line that exists between project types..

A more complex result is illustrated in the multi-variate plot in Figure 5.26. It illustrates the PCT inputs sampled from the log-normal distributions of Figure 5.20. However in this case, the market scenario inputs for first and second mover advantages are no longer discrete. A uniform distribution is given to α_{NL}, α_{DL}, σ_{NL}, and σ_{DL}. The distribution varies from 0 to 1. This is done to provide a understanding of the impact of these parameters from a scenario where the leader in the market receives 0% of the rewards in the duopoly period to where the leader receives 100% of the rewards. The case where the leader receives 0% would simulate a situation where the follower enters the market with a revolutionary engine (technologically more advanced) which would virtually displace its competitor. This would

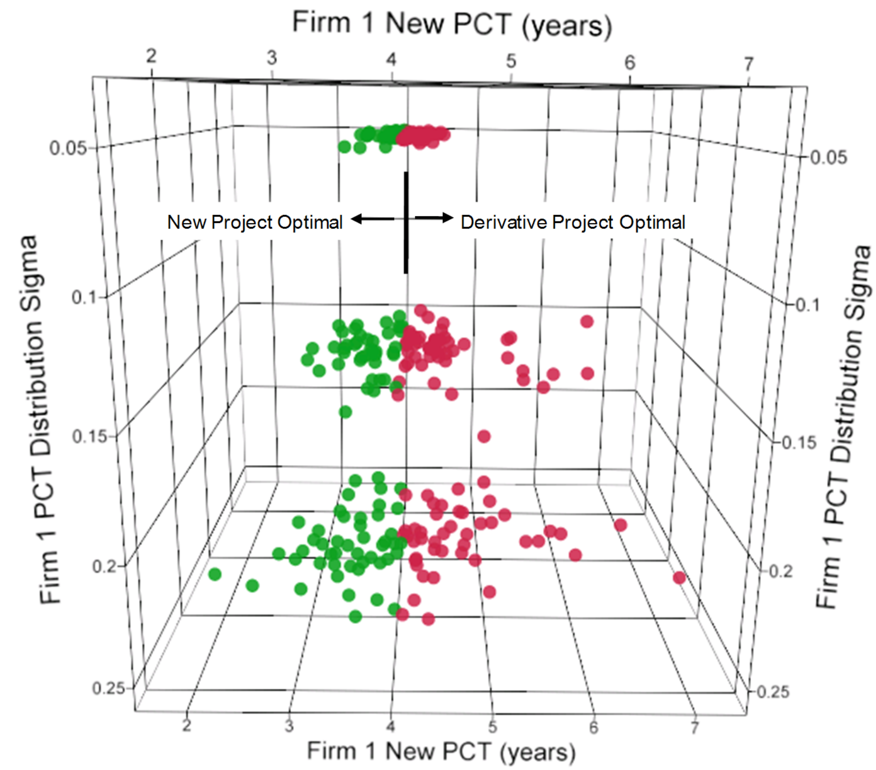

Figure 5.25: Market Scenarios for Three Sigma Values of a New Project PCT Distribution

most likely occur when they are both offering the same type of engine for the same airframe. It is no longer possible to distinguish a clear "switch line" from a new project to a derivative project. For example, in the lower left-hand box of the plot, if firm 1 can estimate that it can complete a new project within 4 years, it is not completely clear if it should commit to a new project because there are some scenarios in which a derivative project may be optimal. There is a region where both new and derivative scenarios overlap. This is where the effects of the first/second mover advantages take effect.

The use of a first and second mover advantage parameter is a useful parameter to envision what-if scenarios in the market. Until this point in the analysis of results these parameters have been fixed such that there are no penalties in the duopoly period regardless of who entered first or second. The reality in commercial aviation is that there exists an advantage (or disadvantage) with respect to the timing of a firm's market entry. The potential rewards of becoming the launch engine for a new aircraft are very large because of the benefits of capturing early customers. Airframe manufacturers like Boeing and Airbus however,

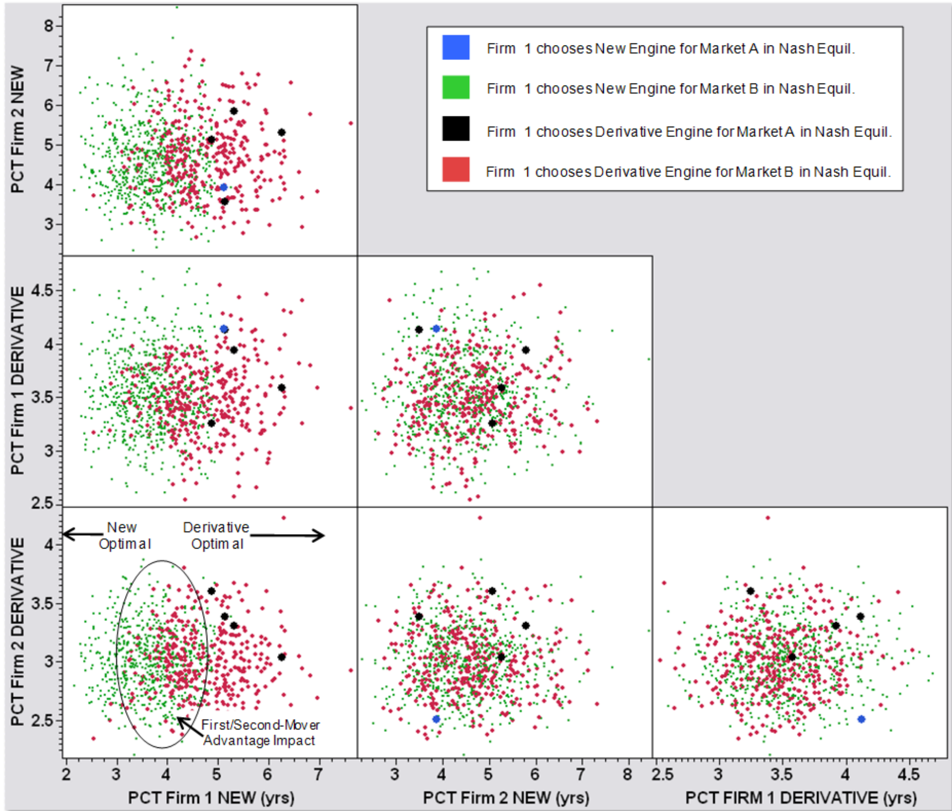

Figure 5.26: PCT Inputs with NE Results of Market Scenario Simulations

would rather have two engines offered on their airframe. This will induce more competition between the airframers since customers will have a larger variety of aircraft performance to choose from to suit their operating structure. Before committing with an engine to the airframer, manufacturers need to determine whether they can successfully develop a particular engine type within their expected project completion time frame. If the market rewards a manufacturer in the duopoly period for having entered the market first with either a new or derivative engine then this is the type of knowledge that would help select the most appropriate type of engine to develop.

5.6.3 Market Timing Results

The next set of results pertain to the impact of having an advantage in the duopoly period when entering the market with a specific engine type. The experiment structure created in this research lends itself to a huge number of possible scenarios to examine. The advantages of using visualization and data manipulation software like JMP provides decision-makers with a tool to dynamically change these first/second mover advantage parameters and quickly observe the impact on engine selection.

The concept of a first or second mover advantage can be viewed as measure of market risk. A firm may be more inclined to enter the market as a leader if there are more benefits than risks when entering first. For example, market leaders will have access to a larger customer base and potentially higher market-share. If however, the technological hurdles are too large or the uncertainty of the market is too great, then entering first can be more risky and firms would have to re-evaluate it's market-timing. The results so far have shown how the uncertainty in project development results in different market-entry scenarios and thus an optimal project choice for each scenario. A further investigation is necessary to model the effects of market risk that are not under the control of the firm. Two cases are presented that demonstrate how these advantage parameters would influence the selection of a particular type of engine.

The first case asks the following question:

- *What happens when both engine manufacturers undertake a new engine program but one is the leader and the launch engine for the proposed airframe?*

The approach to investigate this problem begins by making some key assumptions. First, in order to observe the impact of the first-mover advantage (α_{NL}) the other advantage parameters (α_{DL},σ_{NL}, and σ_{DL}) are set 0.5. This means that in the duopoly period both firms receive a 50% share of the rewards. In Figure 5.27 the plot illustrates how a change in α_{NL} will affect the equilibrium solution of engine selection. The parameter α_{NL} determines how much of the duopoly rewards the manufacturer will receive when offering a new engine into the market. This curve was constructed by training a neural network of 1000 market scenarios. The approximation error is negligible and the model provides a good estimation of the trend that occurs with these advantage parameters. This is verified by carrying out independent market scenario cases by manually changing the parameters and using the Nash

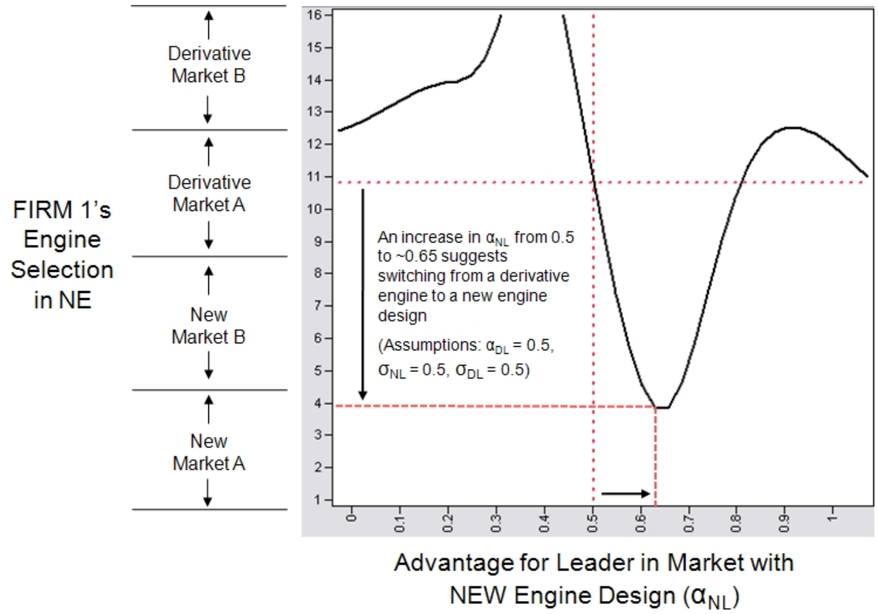

Figure 5.27: Firm 1's Engine Architecture Selection as a Function of Alpha_NL

equilibrium software to evaluate the outcome.

Figure 5.27 has α_{NL} starting out at 0.5. When all parameters are set to 0.5 the resulting equilibrium suggests that firm 1 should design a derivative engine for market A. An increase α_{NL} from 0.5 to about 0.65 implies that firm 1 should switch from designing a derivative engine to a new engine. For example, knowing that firm 2 will propose a new engine design, firm 1 should switch to a new engine design if there is an advantage in entering the market first.

The next case asks the following question:

- *What happens when one engine manufacturer enters the market as a leader but also knows its rival will follow with a derivative engine?*

The situation described here suggests that both firms are planning on entering the market with different engine architectures with firm 1 leading with a new engine and firm 2 following with a derivative. Figure 5.28 illustrates how an increase in σ_{DL} from 0.15 to 1 implies that firm 1 should switch from a new engine to a derivative strategy. This means that as the advantage increases for a firm to lead with a derivative engine (when both firms propose differentiated engine types) the firm with a new engine design should switch to a derivative

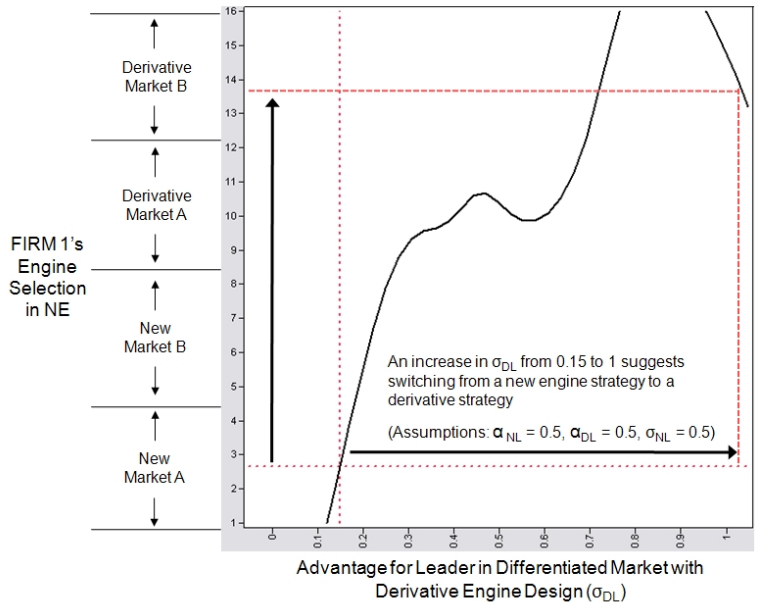

Figure 5.28: Firm 1's Engine Architecture Selection as a Function of Sigma_DL

engine. In this case it is too risky for firm 1 to stay as a leader with a new engine strategy and instead should switch to a derivative design.

The equilibrium results also suggest that firms prefer to invest in differentiated engine strategies when one firm is more efficient in developing a project and therefore will exploit its efficiency to enter the market with that project. Studies by Ali et al.Ali et al. (1993) have demonstrated too that late entrants with access to game changing technologies may have an advantage in developing new project types whereas an incumbent firm would remain with its derivative product as it relies on its experience in the market.

Another finding reveals that when the project completion times between differentiated projects are very staggered (as they are in Figure 5.20) then firms will tend to pursue a differentiated project strategy where they have most advantage in.

Another interesting discovery with the equilibrium results is that as the variability of the project completion times increase for a new project, the equilibrium result tends towards a derivative design. The implication here is that there is potentially more to lose (but also more to gain) in going with a new project than a derivative project.

5.6.4 Risk Analysis under Irrational Competition

After performing an equilibrium analysis on the different market scenarios, various engine selection solutions emerged. However, those results were founded based on several important assumptions. The most important one being that equilibrium solutions are most beneficial when both firms are playing the game rationally. The next analysis does not include an equilibrium calculation but instead uses the concept of risk to determine the best engine choice.

In order to identify how risky a particular engine program might be it is important to understand the definition of risk in the context of this research. In traditional terms, risk is a measure of the likelihood and magnitude of impact of a given event or scenario. In the case of designing aircraft engines, the risk associated with a particular engine could be defined as how much (magnitude) that engine costs to develop or how much the manufacturer stands to lose versus the likelihood that that engine does not satisfy the customer. For example, it would be very risky for a firm to invest in a brand new engine design (typically very costly) knowing that there are many airlines that actually prefer a derivative engine instead.

In the financial field and more specifically according to Modern Portfolio Theory, the risk of a portfolio of investments is measured based on the standard deviation or the volatility of the investments. The model assumes that investors are risk averse and will prefer to invest in the asset with least risk for the same expected return as shown in Figure 5.29. A similar approach is taken in this research which seeks to identify the risk associated with each engine project in order to map a Pareto frontier.

The payoff matrix from Figure 5.18 is used to evaluate the risk of each engine project for firm 1. Figure 5.30 illustrates the payoffs of firm 1 and firm 2. The ideal solution in terms of payoff for each firm would be situated in the top right-hand corner. Maximizing the payoff to firm 1 implies that firm 2 receives a smaller payoff.

The risk of each engine investment is determined by computing the absolute difference in payoff that firm 1 can receive for each engine strategy regardless of what the competition does. In other words, it's the potential loss due to the uncertainty of what strategy the competition might take. Figure 5.31 illustrates the plot of payoff versus risk for firm 1 for

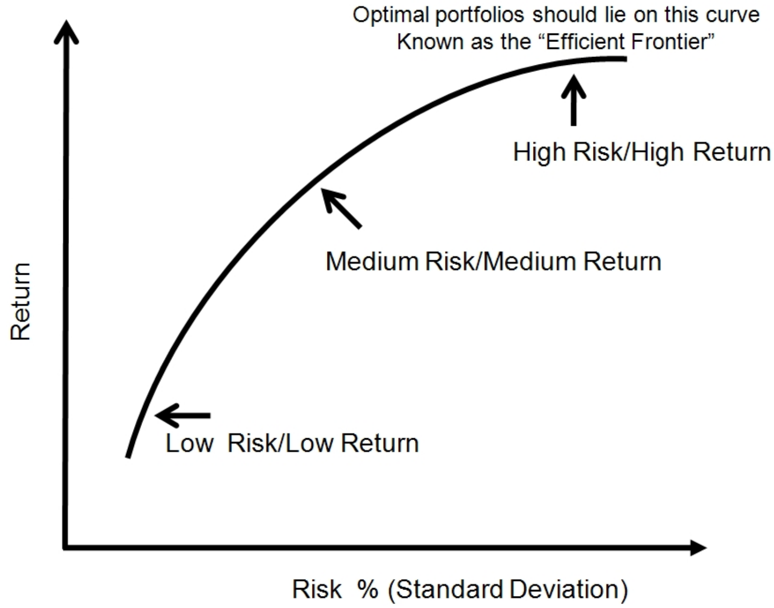

Figure 5.29: Risk versus Return for a Project Portfolio

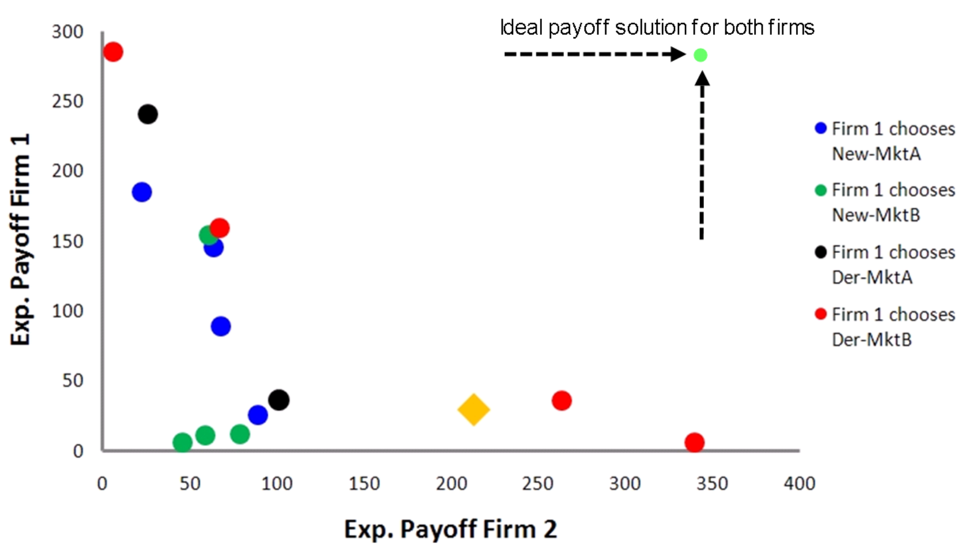

Figure 5.30: Firm 1's Engine Strategies for Fixed Market Scenario

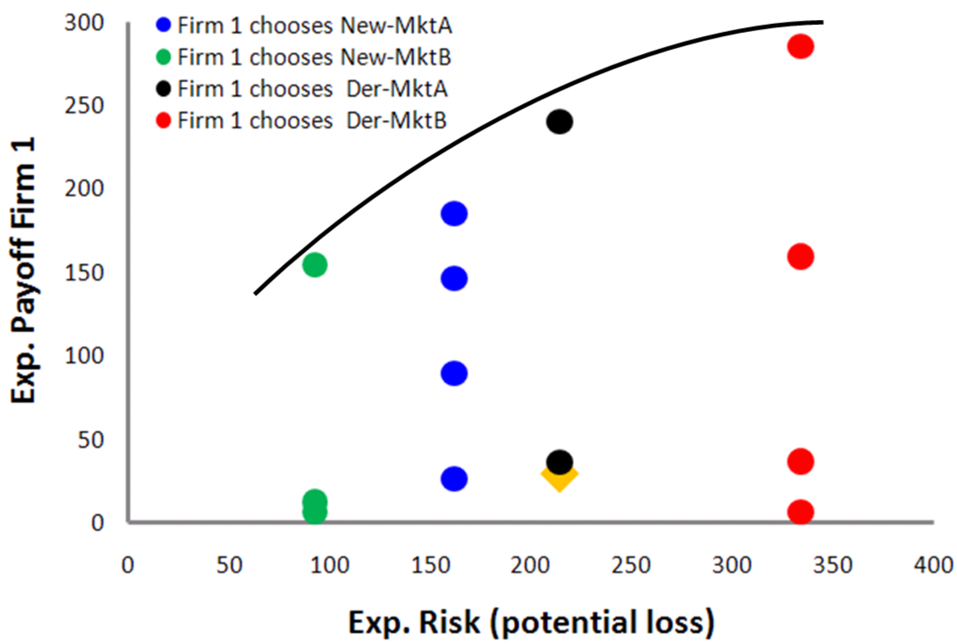

Figure 5.31: Firm 1's Engine Strategy Risk Profile

the four engine strategies.

The results indicate that a new engine for either market A or B is less risky than pursuing a derivative engine design for markets A or B. However, as a result the former engine strategies also will potentially generate less payoff to firm 1.

5.6.5 Decision Factors in R&D Strategy Formulation

The construction of an R&D investment model showed that under rivalry, firms are assumed to maximize their expected rewards under conditions of schedule and market uncertainty. The management literature has shown that firms traditionally make project investment decisions based on potential revenues and development costs via a net present value or return on investment approach. One of the main challenges of this research was to show how managerial decisions must also be made based on the impact of competitors' technical capabilities and how that will influence the choice of project.

It was shown that the project development costs and revenues are key factors in selecting a project to develop as one might expect. However, other considerations were introduced to solidify the optimal project selection. These factors are:

- The relative efficiency between firms in developing a specific type of project (firm characteristic)
- The uncertainty of introducing a project by a given target date (project characteristic)
- The effect of project substitutability in the market (market characteristic)

The assumption of a simultaneous-move game is important in this research but not critical to the key observations made about project selection in general. A sequential approach to project selection would add more flexibility to the firm by introducing a key piece of information, namely the type of project the competitor decided to undertake first. However, the goal in this research was to simulate the initial decision-making that takes place when a manufacturer must commit to the airframe manufacturer with an engine and performance guarantees.

5.7 Discussion of Implementation Results

Throughout each step in the methodology several results were obtained and then transferred to the next step. This section is meant to provide traceability of results from step 1 through step 5.

The methodology begins with a problem definition step that will guide the experimentation process for the subsequent steps. In a QFD analysis the customer requirements of a 300 pax aircraft market are mapped to engineering characteristics from a representative firm to identify which engineering metrics had the largest relative impact on the customer requirements. It was determined that specific engine cycle parameters: thrust, OPR, FPR, etc. had the most significant impact on the requirements that were of high importance to a customer utilizing this type of aircraft. These engineering characteristics and their target values are then transferred to the engine matrix of alternatives to provide guidance in selecting specific values for the creation of an engine design space. Similarly, the customer requirements with the highest level of importance were used to define the pool of airline customer preferences in the customer matrix of alternatives. The QFD results provided the necessary information to populate those two matrices. Both the game matrix and market scenario matrix were designed to provide a broad range of experiment simulations for steps 4 and 5.

In step 2 the generation of engine design alternatives establishes design space to carry out an initial down-selection of engines based on mission feasibility. In step 3 each design is evaluated in the customer value model. There are five airline profiles that were created from the customer requirements matrix of alternatives. Each engine design was evaluated against all five airlines and was given a *value* based on how well it met the preferences of the airlines. The airlines have a specific number of engine orders which, in combination with the engine value, are used to compute the marketshare for each engine.

The game structure and market scenario matrices of alternatives from step 1 are used to establish market scenarios for a two-firm normal-form game. The scenarios specify, through project completion time distributions, the order in which firms will enter the market with a given type of engine project.

In step 4, the market scenarios and marketshare matrices are combined to compute the payoffs for each firm. The result is a 4 by 4 game payoff matrix. This process is repeated 1000 times by sampling different project completion times from each firms' PCT log-normal distributions.

These scenarios are then evaluated in step 5 where the Nash equilibrium is the objective function that determines the optimal choice of engine project for each firm. The choice of engine architecture is examined in terms of its design parameter choices from step 2. This entire loop is illustrated in Figure 5.32.

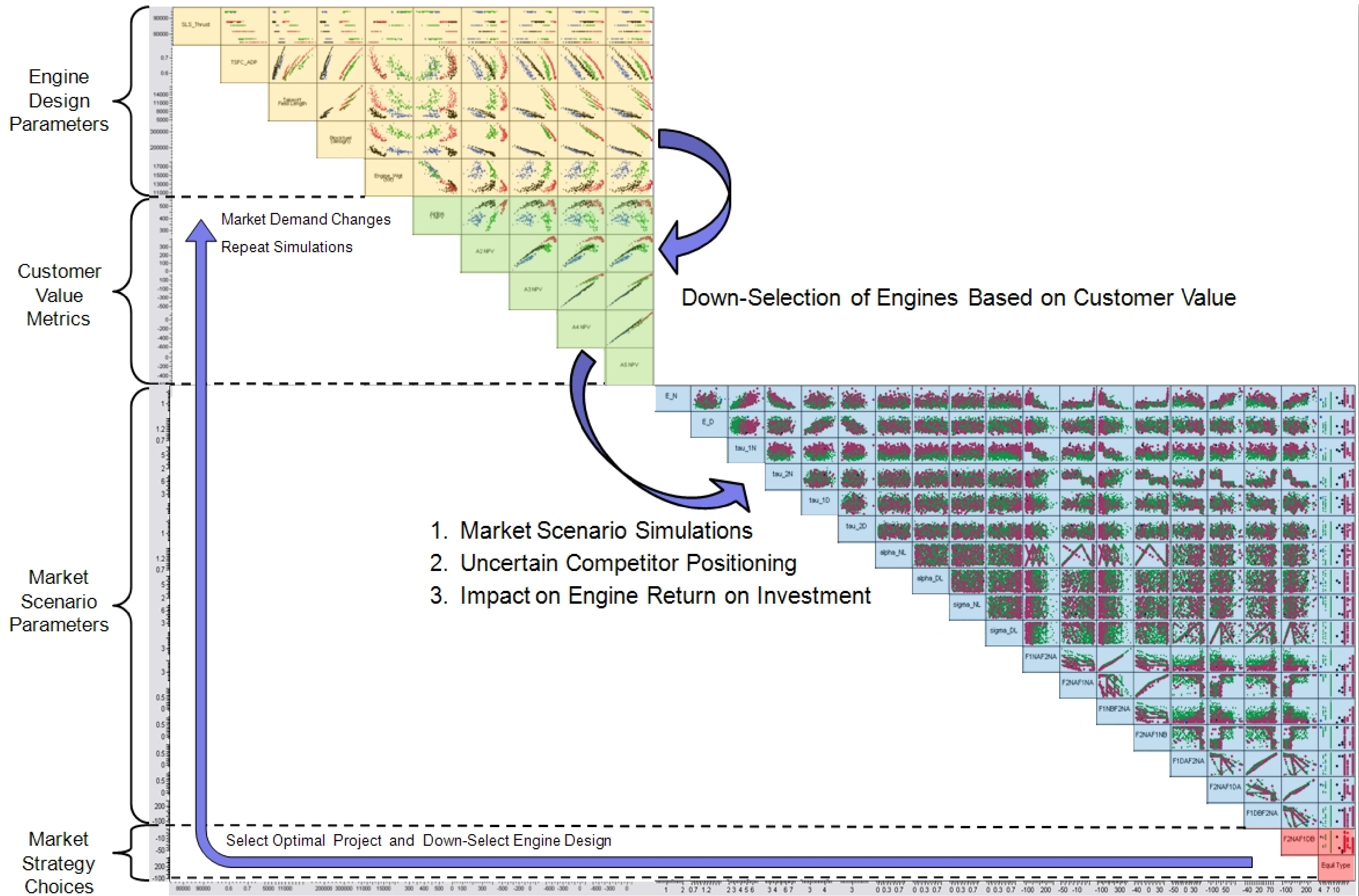

Figure 5.32: Multivariate Plot Illustrating the Mapping of Results from Design Parameters to Market Strategies

Chapter VI

SUMMARY AND CONCLUSIONS

6.1 Summary

The results of Chapter 5 demonstrated how to distinguish engine design concepts from each other based on their competitive value. The result of those experiments was not meant to recommend a specific engine project type to develop. The experiments and results were instead designed as a proof-of-concept to highlight the relationships between engine design and market value. In the end, the results provided a way of visualizing different engine development strategies in an uncertain market environment.

The primary benefit of performing a competitive analysis in conceptual design is to maximize the value in making the right choice of strategy early in the design process. As a consequence, the firm is better positioned for any changes that may arise in the market. The methodology developed in this research adds structure and rationality to the decision-making process. The game theoretic approach also provides a structured way of enumerating options and evaluating them in a quantitative manner. Finally, the global result is being able to drive design decision-making with customer value and business return early in a product's life-cycle.

In section 1.8 of the introduction, three specific objectives were established to bound the scope of the research problem. The first objective was: *Expand the engineering technical design space to evaluate the market performance of large-scale aerospace systems.* Several studies identified from the literature review showed how the design process of consumer products has included a variety of market and competitive analyses. In the aerospace systems design, particularly in commercial aviation, the conceptual design process often lacks the fundamentals of how the business case, previously established, is interlinked with design decisions. A design framework was proposed in this research to bridge some of the gaps that exist in design decision-making. Specific market concepts, like competitor positioning and customer changes, were examined in an integrated environment with key technical design metrics to study the interrelationships.

The second objective was: *Introduce mechanisms that quantitatively model competitive scenarios and their impact on the resource allocation for a portfolio of engine architectures.* This objective dealt with two factors, quantitative competitor modeling and financial investment decisions. The first task was to investigate competitive modeling techniques that primarily provided a means of quantitatively benchmarking competitive behavior. This was achieved via techniques within the field of game theory. The second task was to develop a way of evaluating design concepts financially such that decisions could be made on resource allocation. The two tasks provided a link between the competitor's moves (behavior) and the consequential impact on the investment decisions.

The final objective focused on the design selection process: *Establish a framework for down-selecting engine strategies that accounts for uncertain development periods and that benchmarks potential design performance against the competition.* The concept of market-timing or schedule uncertainty was introduced into the decision mix since there was evidence in the literature that the impact of entering a market as a leader or follower will make a difference on the competitor's choice of product strategy. The framework alluded to in the third objective refers to the game structure in step 5 of the methodology that employs the Nash equilibrium solution as a recommendation of optimal design strategies. This equilibrium approach explores the game design space by evaluating every possible combination of a strategies between players and identifying solutions that may once have been obscured by the complexity of the game.

The methodology developed in this research provided a systematic approach to formulating an engine design strategy for different "what-if" scenarios in a competitive market. The process by which this strategy would be created is summarized in Figure 6.1.

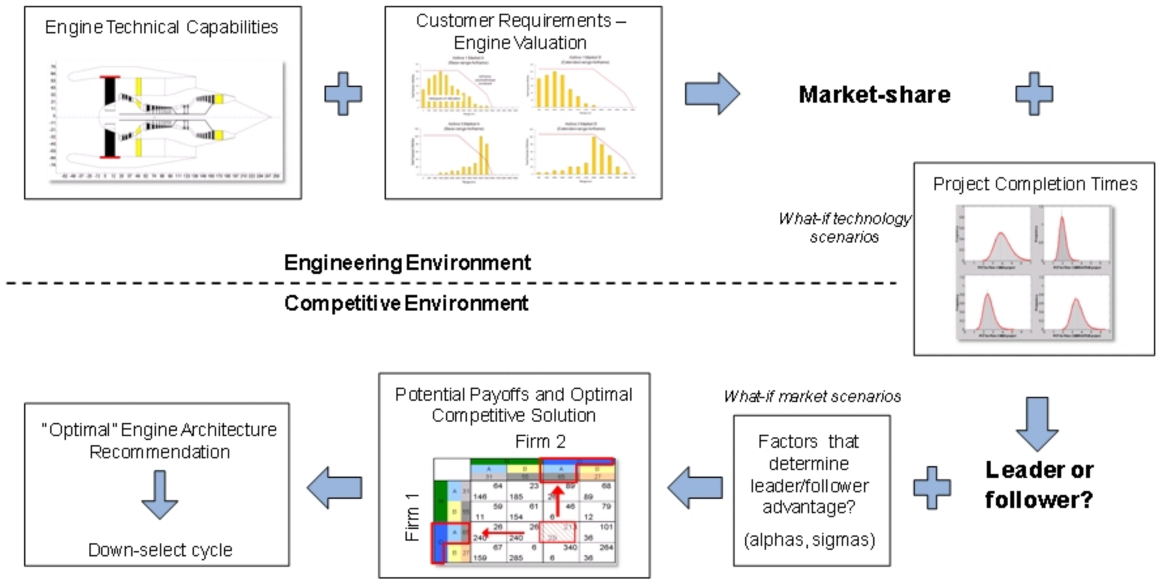

Figure 6.1: Formulating a Competitive Engine Strategy

6.2 Revisitation of Research Questions and Hypotheses

The first research questions were directed towards establishing a framework within the conceptual design of aerospace systems that would include include uncertain market requirements and how these would be mapped to generate feasible designs.

> **Research Question 1.1:** How can the technical design space of complex systems be expanded to model the economic success of R&D programs with uncertain market requirements?
>
> **Research Question 1.2:** How are customer requirements mapped to generate feasible designs and establish value

The first objective and the first question are addressed by the modeling and simulation environment created in step 2 for the engine design space and the firms' payoff functions developed in step 4 which provide an evaluation of the return on investment of R&D projects for fluctuating values of customer requirements. The second question was answered in step 2 with the creation of a customer value model that allows the user to directly map engine design parameters (like FPR,OPR,T4) with customer value metrics (like utilization, payload/range preferences). The customer profiles were established based on different segments in the market, with high or low payload/range requirements or hot and high altitude take-off performance requirements. The proposed methodology provided the direction for answering the first hypothesis:

> **Hypothesis 1:** The uncertainty of market requirements and competition can be quantified within a single unified environment that synthesizes the business case of customer requirements with the performance metrics of designs.

Steps 1 through 3 of the methodology established a way to introduce segmented market requirements and linked them to the generation of engine designs. By employing some game theory techniques that have been proven in a wide-range of fields, a competitive analysis was performed in steps 4 and 5. This assisted in the analysis of uncertainty due to competitive product positioning.

The second research area focused on analyzing competitive uncertainty in different types of markets. It was observed that research and development programs that generate commercial products are very sensitive to market forces. In order to carry out a competitive analysis using the various advanced design techniques, the design problem was converted into a game structure. The second set of research questions were aimed at investigating techniques that could model design problems in a competitive manner.

> **Research Question 2.1:** What competitive decision techniques enhance the confidence in concept down-selection of existing design methods in aerospace systems design?

> **Research Question 2.2:** How can decision-makers quantitatively measure the impact of a competitors product development strategy on the economic success of their design?

The challenge here was to maintain the same or similar conceptual design decision criteria such as thrust, engine weight, fuel consumption (for engine design) and additionally introduce market criteria like competitor payoff, market share, so on and so forth. Chapter 3 provided a broad investigation into the field of game theory and techniques that provided the background necessary to perform these game scenarios. The goal here is to identify a means to quantitatively represent the impact of a competitors' move on a design strategy at the conceptual level. It was determined through the second hypothesis, recalled below, that the utilization of normal form matrix games are representative of competitive situations that provide a platform for making strategic decisions.

> **Hypothesis 2:** Through the use of game theoretic techniques decision-makers can construct a systematic game-based methodology that enhances the design down-selection confidence and mitigates the potential of financial risk.

The third set of research questions and the third focus area were meant to help facilitate the design selection process by investigating different product strategies. The answer to these questions arise throughout the results step 5 in the methodology. The questions below were meant to guide the results analysis process.

> **Research Question 3.1:** What are critical firm attributes that influence project selection under competitive scenarios?
>
> **Research Question 3.2:** What effect does the intensity of rivalry in commercial aerospace systems have on project selection?

The project completion times for each of the firms' projects were critical in determining the payoff values to the firms for different market scenarios.

The structure of the research questions and hypotheses make it so that they build on each other. Therefore, by implementing the methodology via Hypothesis 1 with the mechanisms to evaluate competitive uncertainty in Hypothesis 2 a study of the project selection opportunities under the effects of different competitive scenarios was performed. The game structure in conjunction with advanced probabilistic methods and a well-established modeling and simulation environment provided practical down-selection capabilities in the design process. This was previously formalized into the third hypothesis.

> **Hypothesis 3:** Project development strategies can be formulated using probabilistic techniques in conceptual design thus recommending robust market entry

opportunities and optimal project portfolio selection.

The main effort here tested how different firm characteristics influence the selection of a project and what effect one firm's development attributes has on another firms' project selection strategy. A "best response" formulation was made for a firm given the actions its competitor undertook.

6.3 Contributions and Lessons Learned

The key contribution of this research is the proposed methodology- a game-based decision support method for systems competitive design. This methodology provided a systematic way of quantifying the competitive effects and observing their impacts on the value of different design concepts. The methodology was applied to a commercial engine selection problem for a large passenger aircraft in a highly competitive market.

A second contribution is the formulation of a customer value model that was capable of valuating each design concept in terms of its economic benefit to a customer. In the proof-of-concept experiment, each engine design was evaluated based on its joint performance with an airframe for a given mission mix by an airline customer. The simulation model is capable of handling a wide range of potential airline customer profiles. This is useful to engine manufacturers that want to observe how their engine design might perform under different mission payload/range and utilization scenarios. Several key surrogate models were constructed to provide the flexibility of modeling a broad engine design space.

The third contribution was the inclusion of competitive design techniques directly into the engineering design process. Specifically, the concept of game matrices to evaluate design options under competition and the notion of a mathematical formulation (in the form of a Nash equilibrium) to identify optimal game solutions. These techniques provide engineers with a rational and quick way of visualizing the impact of their design choices on their potential return on investment.

There are also several lessons that were extracted throughout the investigations in this research. The use of a standard discounted cash flow technique cannot fully analyze the *strategic impact* of investment decisions on a firm's future path. It does provide a way of forecasting the economic performance over a set time period but it cannot account for rapid technological changes and the intensity of competition that is more dynamic in nature. The inclusion of flexibility options to account for unpredictable events in the future can be addressed by options theory (discussed in the next section).

The modeling of competitive situations via a simultaneous-move game formulation does not account for decisions that can be made over an extended period of time. This is a major drawback when formulating strategies for R&D development since decisions are seldom made simultaneously by firms. The game matrix could be replaced by a decision tree that would better model the sequential nature of competitive decision-making. This is discussed further in the next section.

6.4 Recommendations for Future Work

The efforts of this research should continue in different ways. Several paths can be taken based on the outcomes observed with the proposed methodology. These can range from refining the existing framework with higher fidelity analyses to introducing additional levels of complexity to the strategic decision-making problem.

Enhancing the Modeling of Schedule Uncertainty

One of the most significant areas of research in aerospace design is the impact of technologies on a systems' performance. Understanding how technologies will impact both the technical performance and economic viability of a system can bring a great deal of knowledge to the conceptual design process. However, this knowledge can be enhanced by understanding how technologies from different firms compete. This enables decision-makers to formulate the best technology strategy when embarking on a new project.

Every technology has a technology readiness level or TRL that is an indication of the level of maturity based on the stage it is at in its development process. These levels could be mapped with the schedule uncertainty to have a more refined estimation of a project's completion date.

Improving the Accuracy of the M&S Environment

There are several refinements that can be made to the engine M&S environment and the customer value models. The use of the EDS platform was beneficial in this research as it provided the experiments with a realistic design space of potential engine candidates. However, several components of the EDS environment were "switched off" in order to reduce the complexity of outputs. In particular, the ANOPP feature, which evaluates the engine noise, was not used. The QFD analysis in step 1 identyfied noise and emissions as being key players in choice of engine design. Therefore, these metrics would be beneficial to include in future assessments of engine designs. The customer value models could likewise be improved by gathering more economic data that could more accurately model the cash flows of both existing airlines and engine manufacturers. This of course has been one the major hurdles in this research.

The use of a normal-form matrix as a game structure in steps 4 and 5 could be replaced with an extensive-form structure to evaluate the sequential timing of strategic decisions. The concept of mixed strategies was introduced briefly throughout the research to demonstrate its value in suggesting more realistic Nash equilbria. In multistage games the notions of threats and commitments are important to model as well.

Evaluating Flexible Strategies

Competitive analysis alone cannot provide all the insights necessary at the strategic level. It is important for both managers and engineers to think in terms of adaptive strategies that may help address questions like: what is the value of growth opportunities and when does it make sense to maintain a "wait and see" approach? Is a joint research venture or strategic alliance more valuable in the long term? These are precisely the questions that need to be asked that will help determine a firm's competitive success but are made in the absence of structured and quantitative analyses. Valuation methods like Real Options have emerged as a way utilizing financial options pricing mechanisms to quantify the strategic adaptability options, like expanding into new growth markets. The combination of Real Options and game theory has provided a means to analyze the effect of uncertainty on the value of an

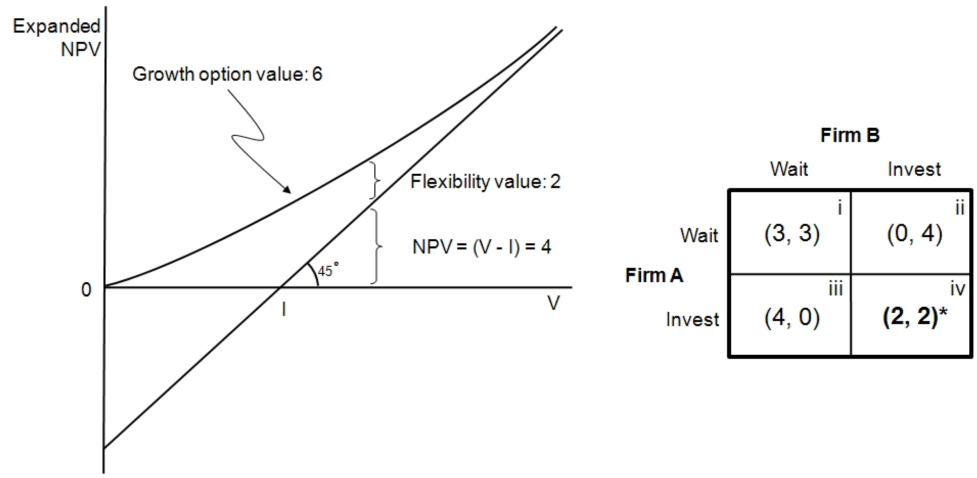

Figure 6.2: Example of an Option Game (Smit and Trigeorgis (2004))

investment opportunity. Smit and Trigeorgis (2004) describe how a "wait and see" strategy would play out in Figure 6.2. Two firms have an investment opportunity in a market with a total value of 4$ billion. The value of the "wait and see" option under demand uncertainty is 2$ billion which results in a total market net worth of 6$ billion. The right-hand side of Figure 6.2 depicts a game matrix with payoffs to firms A and B for two options, wait and invest. There are four possible scenarios where they either: (i) both wait and equally share the profits of \$6B, resulting in a (3,3) payoff, (ii/iii) one firm preempts the other and invests, receiving the existing market value of \$4B while the other receives \$0, (iv) or both invest immediately (simultaneously) and share the market value resulting in a payoff of (2,2). The game results in a Nash equilibrium outcome where both firms invest and receive a payoff of \$2B each. This is example is similar to the prisoners dilemma where both firms would be better off by coordinating their strategies and exercise the option of waiting until the market value increases to \$6B.

Competitive strategies can therefore be analzyed using both option valuation methods with game theoretic principles. The strategic value can be obtained through a holistic framework that introduces an expanded NPV criterion to capture the strategic commitmetn value of competitive interactions.

Product Management and Information Technology Areas

Further studies in the areas of product life-cycle management (PLM), supply-chain management (SCM), and enterprise resource planning (ERP) could benefit the upfront analysis of selecting R&D projects. The goal is to further integrate the business practices with the engineering processes to improve product quality, reduce time-to-market and become more efficient at manufacturing products. Elements within those practices could lend themselves to a competitive framework like the one proposed in this research.

Appendix A

MARKET SCENARIO RESULTS

A.1 Engine Manufacturer CashFlows

In the market scenario simulations in step 4 of the methodology variations in first and second mover advanatages were examined to identify how the payoff for each firm would change based on these external market factors. In this section some results are presented for scenario simulations of cashflows for different values of first-mover advantage for a leading firm with a new project. Figure A.1 illustrates two cashflow plots. The top one is a simulation of of the different Alpha_NL values. The effect on the cash flow takes place after the monopoly period since it is at this point where both firm would split the market rewards. The bottom plot in the figure illustrates the cumulative cashflow as well as the individual future cashflows at each year in the production period. The red stems represent the cashflows in the duopoly period.

A.2 Global Multivariate Snapshots

The multivariate plot in Figure A.2 illustrates the main engine technical metrics: SLS_Thrust, TSFC at the Aero-Design Point, TOFL, BlockFuel (design), and engine weight. In addition to these metrics the results for the Net Present Value of Airlines 1 through 5 are also presented. The results are categorized into four groups representing the four different engine options available to each engine manufacturer: New engine in market A (blue), New engine in market B (green), Derivative engine in Market A (black), and Derivative engine in market B (red).

The multivariate results in Figure A.3 show the 1000 market simulations of different project completion times (PCT's) for the four different engine projects (listed in the previous paragraph). The input metrics for PCT and the first/second mover advantage metrics are presented in addition to the payoff outputs for each possible combination of project. The last

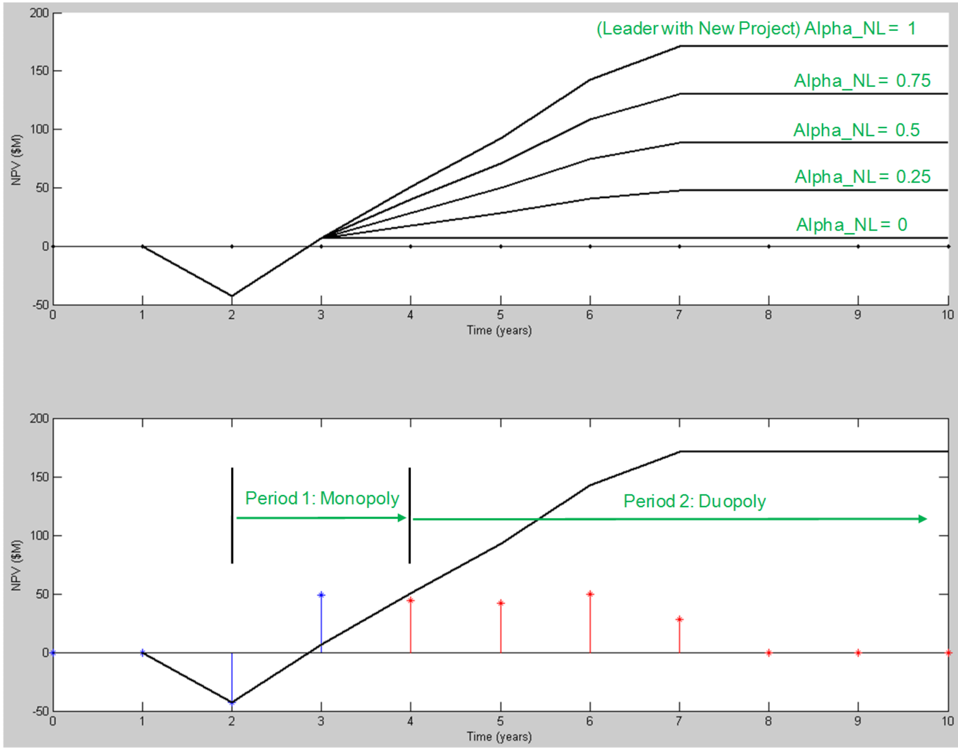

Figure A.1: Leading Engine Manufacturing Firm Cashflows for Different Alpha Scenarios

metric is the equilibrium type which signifies the Nash equilibrium result for each market simulation.

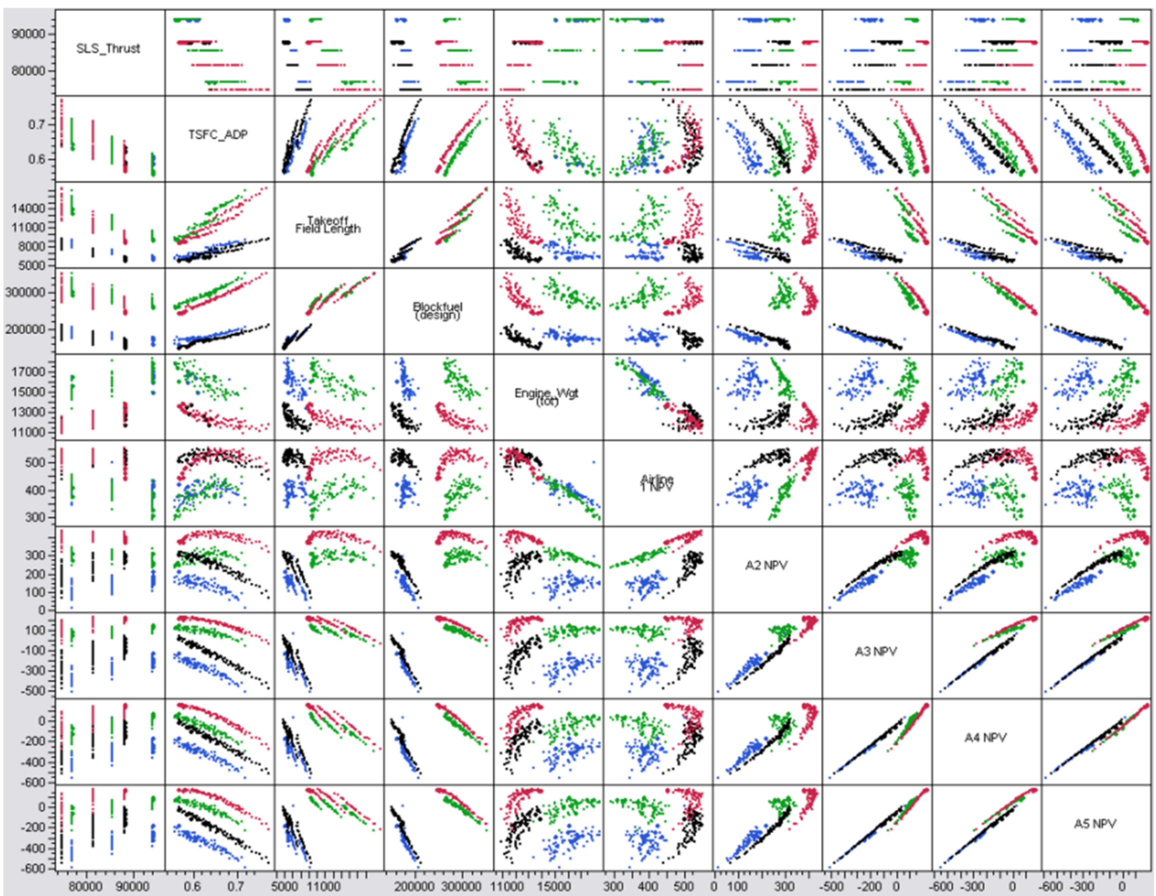

Figure A.2: Multivariate Plot of the Engine and Customer Value Metrics from Steps 2 and 3

Figure A.3: Multivariate Plot Illustrating the Market Scenarios and Equilibrium Results from Steps 4 and 5

Appendix B

SURROGATE MODELING TECHNIQUES

The use of surrogate modeling techniques has become more and more evident in many engineering design problems. This is particularly the case in the aerospace industry where engineers use complex analysis codes for large-scale systems. These codes are beneficial since they provide decision-makers with the necessary data and information to make key observations about the behaviors of a system that are often too complicated for a human to do by hand. Oftentimes however, in conceptual design, the problems are poorly defined and there is incomplete information. When this is the case engineers can run the analysis codes multiple times under varying conditions to provide a healthy design space to examine. The necessary computer power to run these codes at all the key conditions is quite substantial, even for modern computers and simple design concepts. The purpose of surrogate models is to create a "model of model", or a metamodel of the analysis code. This new model approximates the behavior of the real analysis code. Several surrgoate modeling techniques exist but this research employed both response surface methodology and neural networks. These are described in the next two sections.

B.1 Response Surface Methodology

Response surface techniques are based on creating empirical models to approximate a system's behavior. Their explanatory power is limited by the scope of the data used to create the model. The most common response surface equation is a linear, second order polynomial equation based on a Taylor series approximation. An example is shown in equation B.1.

$$R = b_o + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j + \varepsilon \qquad \text{(B.1)}$$

The parameters in the equation are: R is the response, b_o is the response intercept, b_i is the coefficient for the first order terms, b_{ii} is the coefficient for the second order terms, b_{ij}

is the coefficient for the cross terms, and x_i and x_{ij} are the independent variables and ε is the error term. The coefficients b_i, b_j, and b_{ij} are typically calculated with a least squares fit. The response is estimated for different combination of x_i variable in the model. The optimal combinations of design variables is created by using three level DoEs but they can also be created using more levels of resolution. Response surface equations are not capable of modeling non-linear behaviors in systems or discrete responses. For this reason the help of Neural Networks is becoming more and more widespread in modeling aerospace systems.

B.2 Neural Networks

Neural Networks are a popular surrogate modeling technique based on the biological functions of the brain. The process works by mapping a set of input variables to a set of responses through a set of filters, called hidden layers as illustrated in Figure B.1 as described by Johnson and Schutte (2006). The first layer is the input layer and it contains the model inputs. The output layer contains the responses and the layers in between are called the hidden layers.

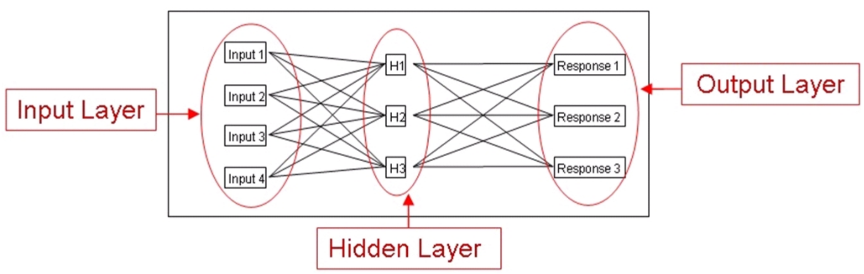

Figure B.1: Neural Network Conceptual Diagram

Appendix C

BASE-CASE PAYOFF RESULTS

The PCT values are shown in Figure C.1. The figure is divided into the 4 game cases. Each dot represents one game scenario (1000 total). The game scenario highlighted in red represents a combination of 4 PCT's, $[\tau_{1N}, \tau_{2N}, \tau_{1D}, \tau_{2D}]$. The model computes the payoffs for each scenario and calculates the Nash equilibrium for that scenario. There are four pure Nash equilibria possibilities. A scenario where both firms choose *new* in equilibrium is highlighted in blue. Firm1 should choose *new* and firm 2 should choose *derivative* when scenarios are green, *derivative* and *new* when scenarios are black, and both firms should choose a *derivative* project when the game scenario is red. These equilibria results indicate that projects that tend to be introduced into the market fast are preferable since they will likely yield higher payoffs. The determination of the equilibria however, is driven by who is leader and who is the follower. So the relative introduction of projects into the market between firms has a more significant impact on the payoff than the speed at which an individual project is completed.

The second test case in the base-case model adds four more independent variables: $[\alpha_{NL}, \alpha_{DL}, \sigma_{NL}, \sigma_{DL}]$. These are the first/second-mover advantage parameters that alter the payoffs of each firm to observe how the project choice changes when a firm is a leader or a follower in the market. In a verification experiment, σ_{NL} and σ_{DL} are set to 0.5 so the focus shifts to just looking at scenarios where firms enter the market with *similar* products, i.e. [N,N] or [D,D], with advantages, α_{NL} and α_{DL}. Figure C.2 is a plot of the game scenarios for the second base-case test. The red points represent game scenarios where both players should enter the market with a new product and the blue points are those where firms should enter with a derivative product. The results show how an increase in the first-mover advantage in the market for either project type beyond 0.6 will suggest that each firm choose the project with higher leader advantage to develop. For example, in the lower

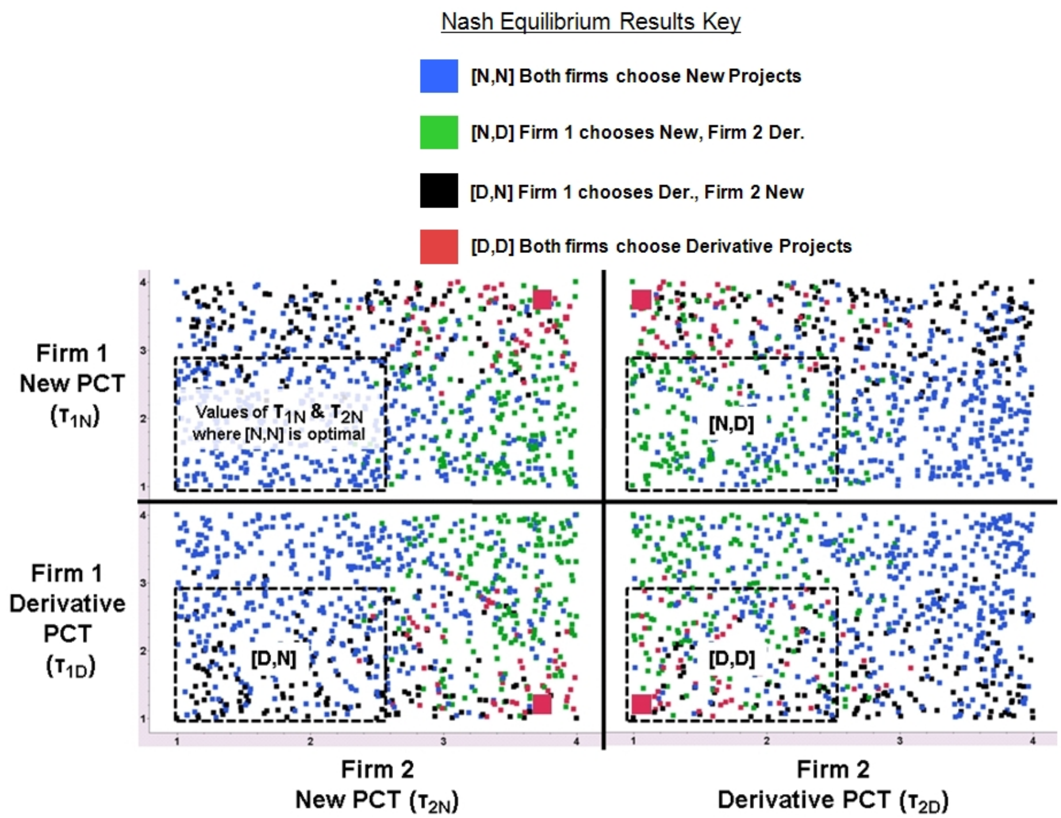

Figure C.1: Base-case Game Scenarios with Nash Equilibria

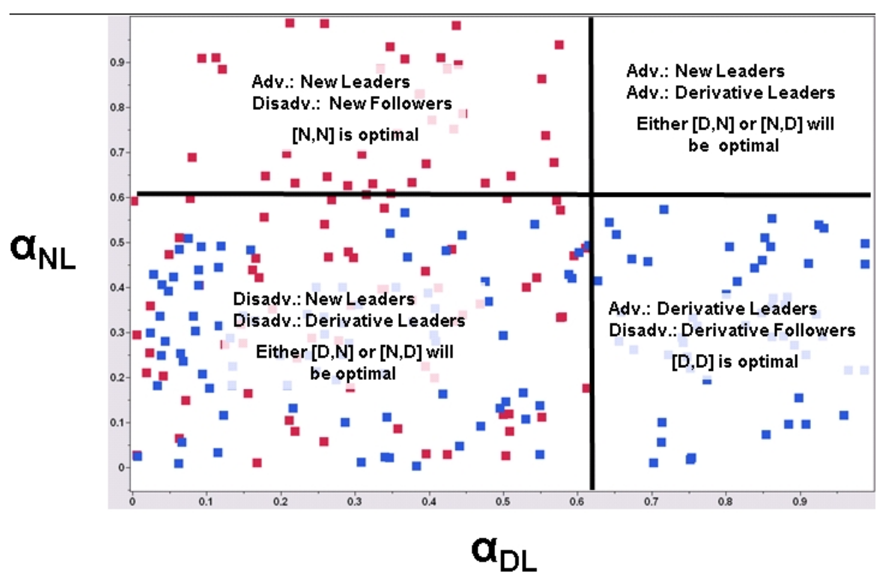

Figure C.2: Base-case test 2 [N,N] and [D,D] Equilibria for different Alphas right-hand quadrant there exists a large market advantage for leaders of derivative products but a disadvantage for leaders of new products. It is assumed both firms enter the market with similar products so in this case they would enter with derivative products.

Appendix D

SUPPORTING LITERATURE

D.1 Five Forces Model and Best Response Correspondence

Porter developed a competitive analysis framework consisting of five main factors that determine the attractiveness of a market. He then provides an approach for competitor analysis by first creating a competitor intelligence system. "The knowledge of each competitor's probable moves and capacity to respond to change can be summed up, and competitors can be seen as interacting with each other on a simulated basis" (Porter, 1998). The goal of the intelligent system is to collect data about the competition, compile it and formulate strategy accordingly. A variety of recommendations on how to proceed at each step is given.

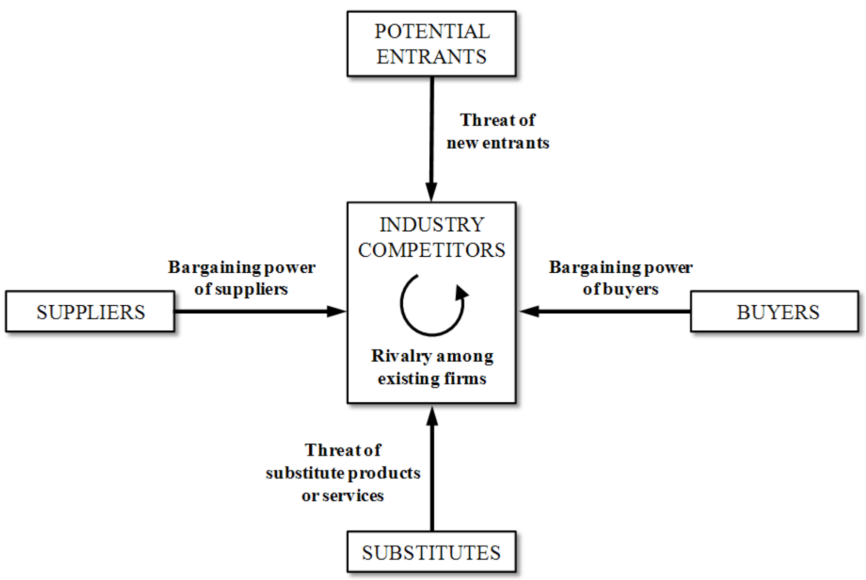

Figure D.1: The Five Competitive Forces That Shape Strategy (Porter, 1998)

The Best Response Correspondence (BRC) is a technique in game theory that produces a strategy which describes the most favorable outcome for a player. This technique has been applied to design problems for different optimization problems. Figure D.2 is an example process of how to create a BRC. The exact equations of the best response correspondence

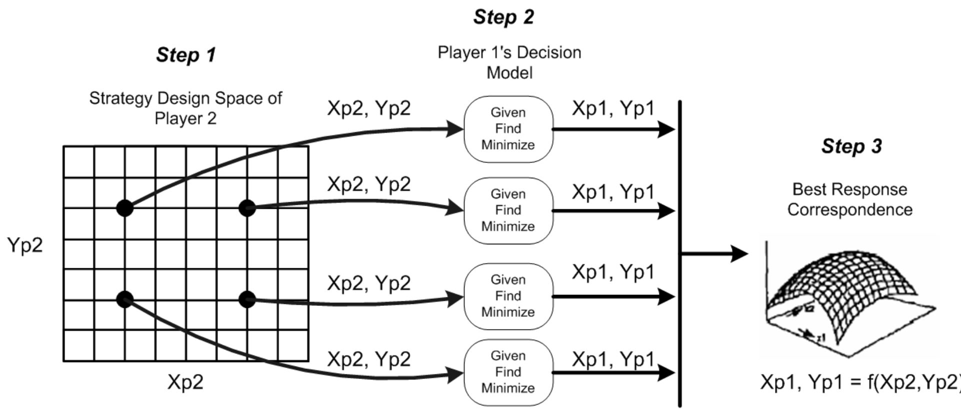

Figure D.2: Best Response Correspondence Approach (Hacker, 1999)

are difficult to obtain for highly nonlinear problems. It is often difficult to develop a closed form equation for one or more variables as functions of other variables. Therefore, the BRC of players is typcially found using approximation techniques or surrogate models such as response surfaces or neural networks.

D.2 Boeing 777 Aircraft Engine Market Trends

The following charts illustrate the Boeing 777 engine sales for each individual aircraft derivative. The sales are based on year in which deliveries were made to the airlines.

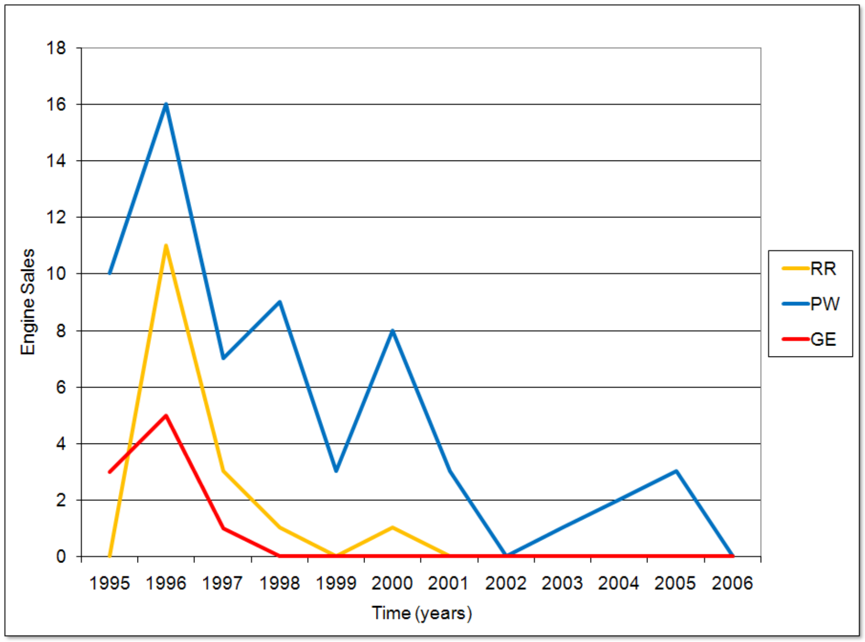

Figure D.3: Boeing 777-200 Engine Sales (Deliveries) (Boeing Commercial Airplanes, 2008)

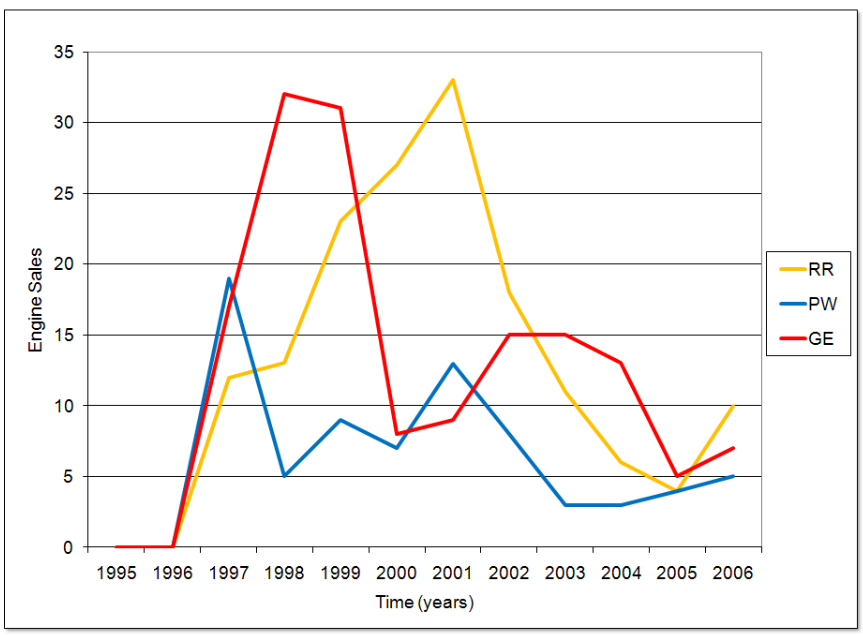

Figure D.4: Boeing 777-200ER Engine Sales (Deliveries) (Boeing Commercial Airplanes, 2008)

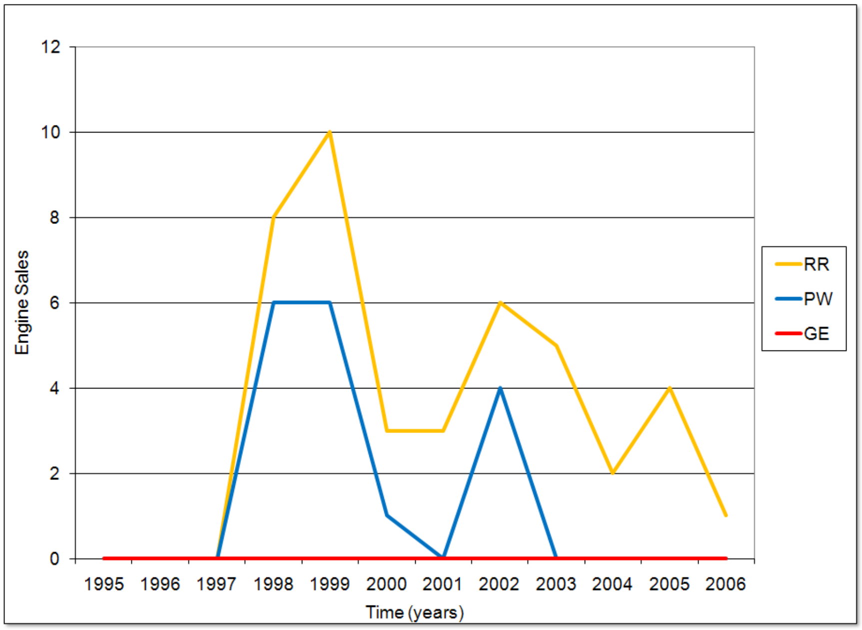

Figure D.5: Boeing 777-300 Engine Sales (Deliveries) (Boeing Commercial Airplanes, 2008)

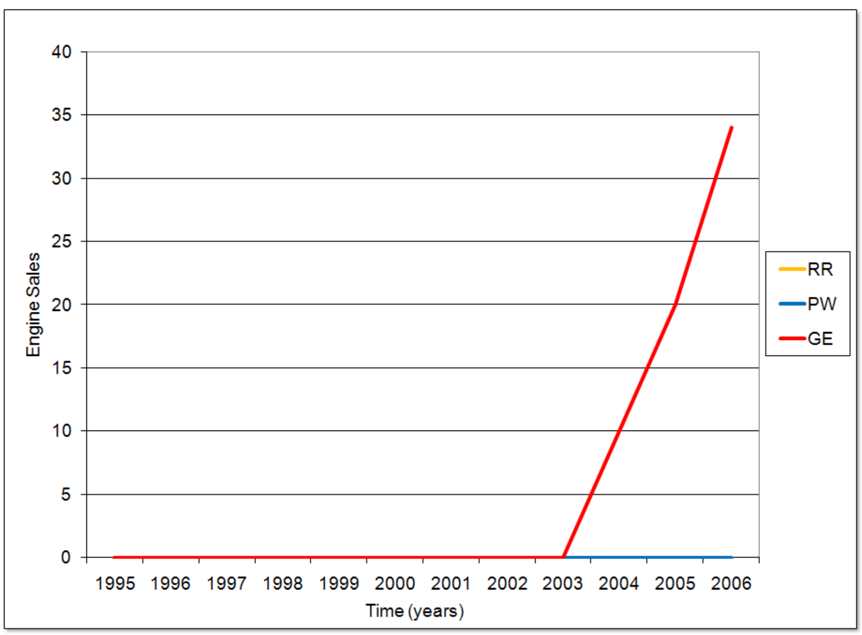

Figure D.6: Boeing 777-300ER Engine Sales (Deliveries) (Boeing Commercial Airplanes, 2008)

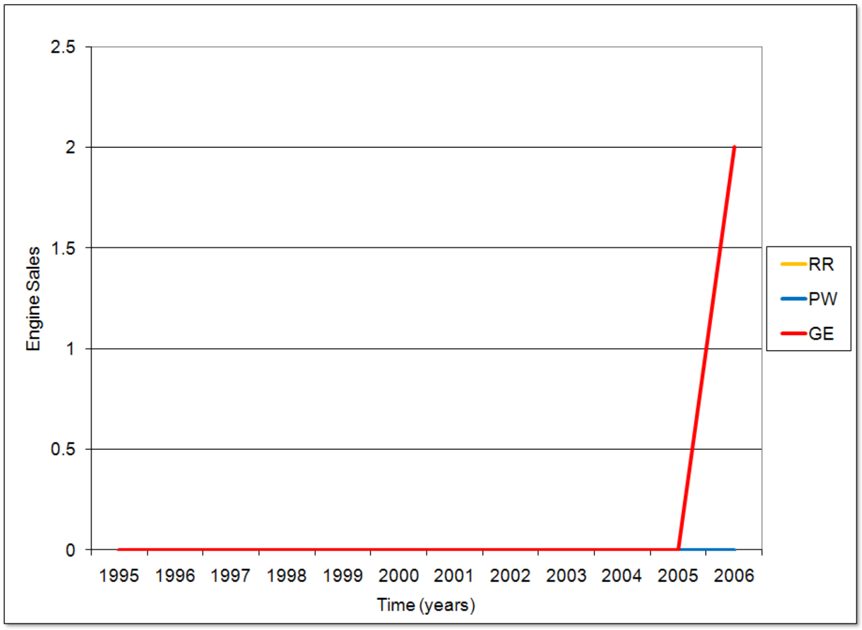

Figure D.7: Boeing 777-200LR Engine Sales (Deliveries) (Boeing Commercial Airplanes, 2008)

D.3 Customer Value Modeling

A customer value graphical user interface was created for an engine selection study to down-select engine designs based on payload/range preferences for customers.

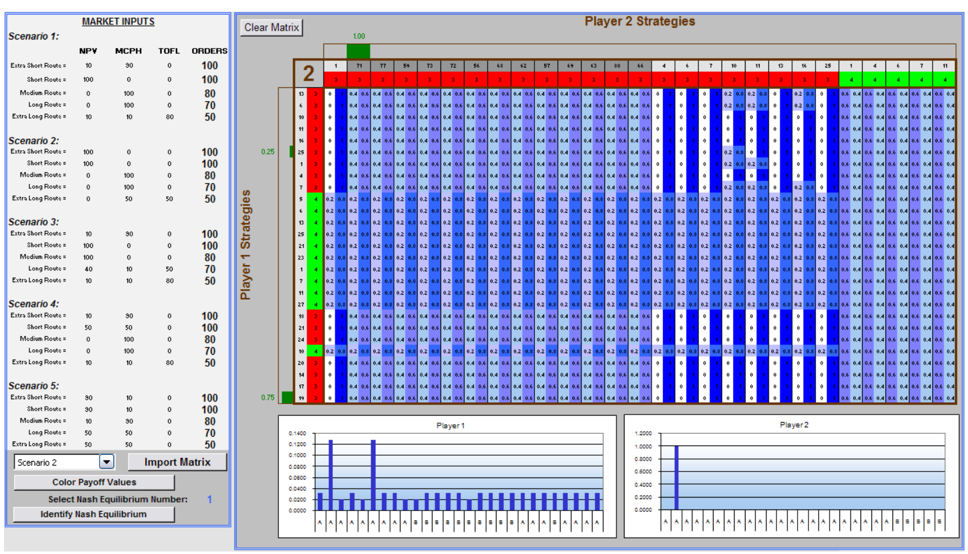

Figure D.9: Payoff Matrix and Nash Equilibrium Modeling Tool (Excel)

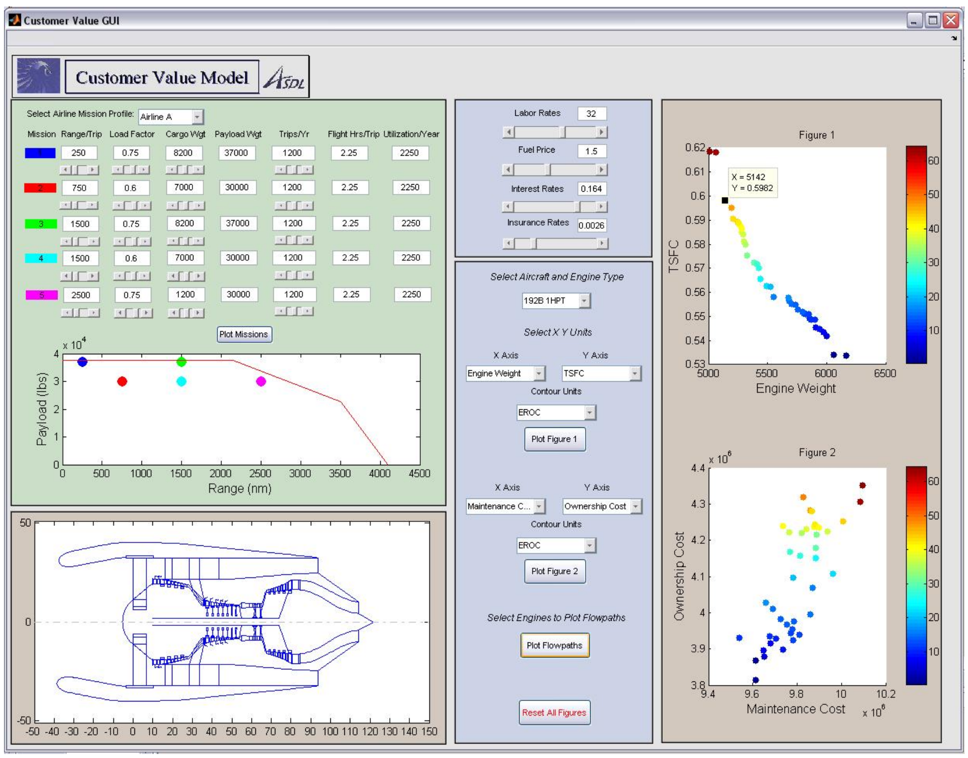

Figure D.8: Customer Value Interface Model (Matlab)

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VITA

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